Chapter 1
Introduction

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1.1 Motivation for Increased Communications

This monograph represents the collective knowledge and experience of more than 25 years of concentrated research and development effort by a dedicated team of talented technologists at the Jet Propulsion Laboratory (JPL). The work began in the late 1970s and continues today. The vision was an optical communications capability that provides orders-of-magnitude more data return from deep-space missions than is possible with conventional radio frequency (RF) techniques, and the dream has been to see that capability being matured, demonstrated, and used operationally within the professional careers of those who contributed to its earliest analytical and experimental developments.

Communication over deep-space distances is extremely difficult. Communications beams spread as the square of the distance between the transmitter and the receiver. As the distance increases, the difficulty becomes quadratically more difficult. For example, conventional satellite communication from Earth orbit often uses satellites in geosynchronous Earth orbit (GEO) to communicate with the ground. The GEO altitude is approximately 40,000 kilometers (km). From such a distance, quite high data rates in the gigabits per second (Gbps) can be established and maintained. However, the distance from Earth to Neptune or Pluto can be on the order of four billion (4,000,000,000) km. After propagating over such a distance, the communications beam from a spacecraft will spread to an area 10 billion times larger in area than if the beam from the same system traveled from just the GEO distance. The weakened beam would make communications with the Earth 10 billion times more difficult. Stated differently, a system capable of transmitting 10 Gbps from GEO to the ground would only achieve 1 bit per second (bps) from nominal Pluto/Neptune distances.

One could, of course increase the capabilities of the distant spacecraft's communications system, as well as improve the sensitivities of the Earth reception systems. Indeed, both of these approaches are used for present-day deep-space missions. The net effect has been to raise the nominal data rates from Mars distances to the range of tens to hundreds of kilobits per second (kbps), with correspondingly lower data rates for the outer planets. But further increases are hard to accommodate. Current missions are already flying antennas that are difficult to squeeze into protective launch shrouds, and increases in transmitter power are discouraged due to the difficulties of both generating electrical power at far solar distances as well as removing the waste heat resulting from the corresponding inefficiencies of the various transmitter energy conversion components. On the Earth end, increasing sensitivity is likewise difficult. Current National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) antennas are already enormous (34-m and 70-m diameters), and the receiving system low-noise amplifiers are already operating at but a few degrees above absolute zero. More advances in conventional communications capabilities are planned, and even larger improvements are being researched for future consideration, but practical realities will eventually limit the degree to which such improvements can be made.

As an example, consider the Mars Global Surveyor (MGS) mission that was, and continues to be, an outstanding success mapping features of the Martian terrain. During the entire prime mission phase, the project was only able to map 0.3 percent of the Martian surface at high resolution. More has been mapped during the extended mission phase, but even with this extension, the mission will produce high-resolution maps of only a few percent of the surface. This coverage has been limited by the capabilities of the communications system that was affordable at the time the mission was defined and developed.

Although conventional capabilities will likely rise in the future, so will the needs for even higher instrument data volumes. Most of the planets have had initial flyby pathfinder missions, and a few have had initial-characterization orbiters. However, the spatial and spectral sensitivities of those instruments have been very limited by the data-return capabilities and are orders-of-magnitude below what scientists are doing for Earth observations today. Figure 1-1 shows these future needs. The horizontal axis is the data rate, and the vertical line near the left side is the MGS capability when scaled to Saturn distance. The vertical dimension has no meaning other than to show that things

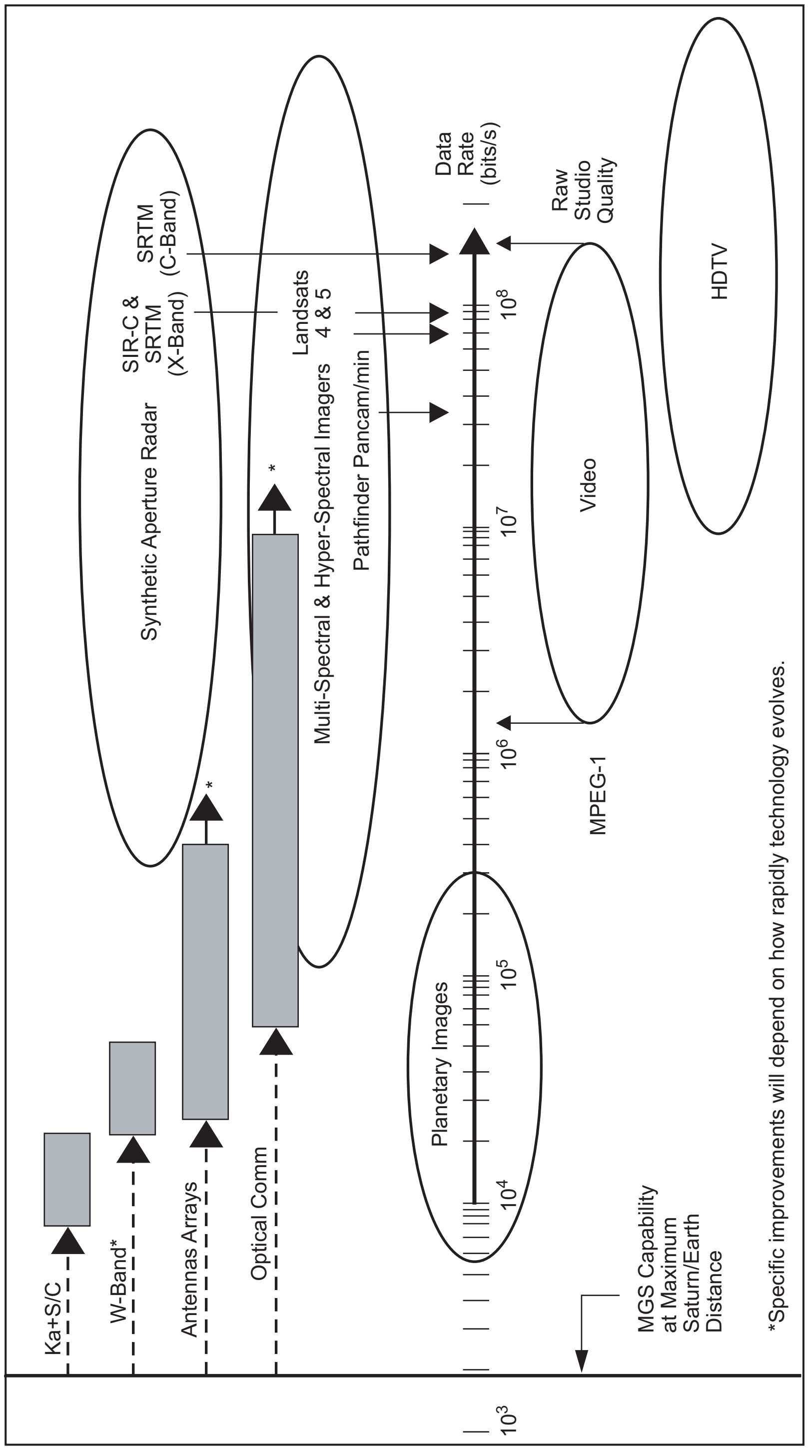


Fig. 1-1. Future data return needs relative to current capabilities based on Mars Global Surveyor at maximum Saturn range.

above the central data-rate-axis arrow are representative of scientific investigation needs, whereas those below just provide a rough measure of telecommunications needs for enhanced public engagement. The ovals represent horizontal data rate regions where corresponding instruments are expected to operate. Regions of anticipated capability improvements are shown for several candidate communications technologies. Technologies ultimately chosen and how far to the right those improvement bars can be extended depend on current and planned technical research and system designs, as well as thorough life-cycle-cost analyses. However, the anticipated performance capability improvements of optical communications are clearly evident.

The promise of improvement comes, to first order, from the much higher frequencies of the optical signals. Over the history of the DSN, conventional RF performance has improved about 12 orders-of-magnitude due to significant and sustained research and development (R&D) efforts at JPL. Improvements have come from many technological advances. However, the biggest improvements were achieved when the operating carrier frequency of the communications signal was increased. Currently, the primary frequency used for deep-space communications is X-band (approximately 8 GHz), although new missions will soon be transitioning to Ka-band (32 GHz). The change from X-band to Ka-band has a theoretical improvement (due to frequency-squared) of 11.6 dB, although practical factors (e.g., atmospheric losses) have limited that improvement to about 6 dB. The promise of optical communications is much more since the frequency is very much higher (approximately 300,000 GHz). Although practical factors (e.g., atmospheric losses, receiver sensitivities) will also be present, they are more than offset by the frequency-squared benefit of the higher carrier frequency.

Figure 1-2 diagrams the much lesser beam spread offered by optical transmission. The left side of the figure shows the transmitted beam sent back toward the Earth from the Voyager spacecraft. The transmitting antenna is 3.7 m in diameter (a dominant architectural feature of the spacecraft), and the transmitted frequency is X-band. By the time the beam reaches Earth from Saturn, diffraction (a fundamental property of all transmitted electromagnetic beams) has caused the signal to spread out over an area 1000 Earth-diameters wide. Contrast this with the right-hand side of the figure where the beam from a small (10-cm) optical telescope is transmitted back to the Earth. Assuming an optical wavelength of 1 μm (frequency of 3×10^{14} Hz), the resulting spot size at the Earth is only one Earth diameter wide. That represents a factor of 1000 concentration of the received energy in both the horizontal and vertical directions (factor of 10^6 in power density), and that is achieved with a very much smaller transmitting antenna (0.1 m versus 3.7 m) on the spacecraft. The wavelength-squared advantage over X-band is approximately 90 dB, although quantum effects and practical implementation considerations limit current realistic gains to about 60 dB.

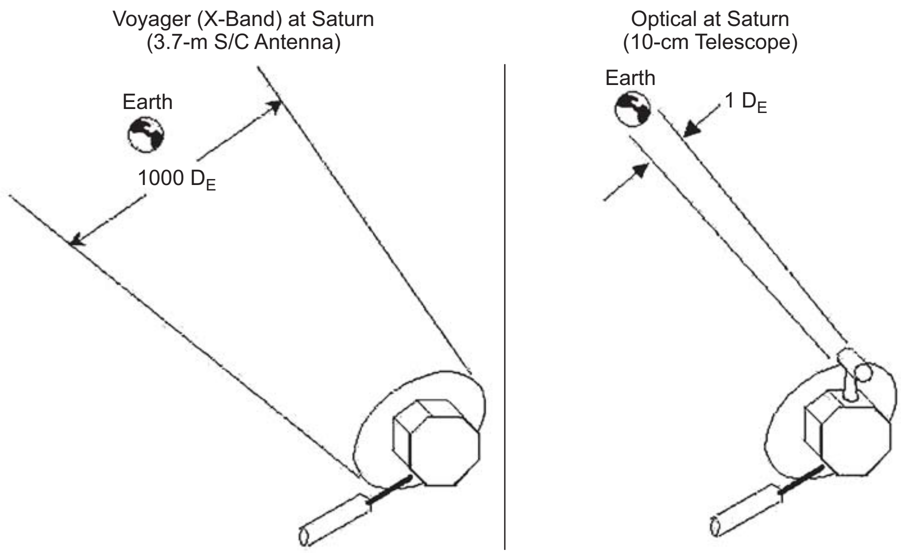


Fig. 1-2. Comparison of RF and optical beam spreads from Saturn.

1.2 History of JPL Optical Communications Activities

JPL began considering optical communications in the late 1970s. Dr. John R. Pierce was the JPL Chief Technologist at the time and had been looking into some interesting attributes of quantum detection theory. In 1978, he wrote a paper predicting that multiple-bit-per-photon optical communications appeared to be possible [2]. Unlike conventional RF communications that used phase modulation of the carrier, Pierce suggested using direct photon detection with a high-alphabet pulse-position modulation (PPM). PPM modulation uses a time interval that is divided into a number of possible pulse locations, but only a single pulse is placed in one of the possible positions. The position of that pulse is determined by the information (word) that is to be transmitted. Given the experience JPL had in deep-space communications, the prospect of extremely power-efficient communications looked very attractive. However, to realize the potential of multiple-bit-per-photon optical communication, it would be necessary to use codes that were efficient at filling in channel erasures. The model for the optical channel under these circumstances was a pure erasure channel where the dominant error source was the quantum uncertainty of the signal itself, and this resulted in pulses for which the weak received photon field contained inadequate probability to reliably constitute detection of a received photon. The laws of quantum mechanics dictated how often these pulses would be “erased.” Thus, contextual information (i.e., codes) that bridged these erasure events would be required.

At the time, JPL was routinely using Reed–Solomon (RS) codes in concatenation with convolutional codes. The RS codes were very efficient at correcting the bursts of errors that would result when the Viterbi decoder that was decoding the convolutional code made an erroneous branch path decision. Since the loss of a single PPM optical pulse detection caused a similar burst of errors (loss of a pulse meant that the data bits associated with that pulse were chosen at random), it appeared that such codes were well matched to the PPM channel.

To prove this out, a technology task was started to demonstrate multiple-bit/detected-photon communications in the laboratory. At the time, the heterodyne detection "quantum limit" was understood to be 1 nat/photon (1 nat = 1.44 bits), and this limit was believed to apply to all optical communications systems. However, Pierce in [2] was predicting that much higher photon efficiencies could be achieved. Accordingly, the objective selected for the technology task was 2.5 bits/detected photon, a comfortable margin beyond the classical quantum limit.

Figure 1-3 shows the experimental setup that resulted. Inside a light-controlled enclosure was a semiconductor laser diode, some calibration detectors, calibrated optical attenuators, and a cooled photo-multiplier tube (PMT) detector. The laser diode was driven by the signal from a PPM modulator.

The output of the PMT detector was integrated over the time intervals of each of the possible pulse locations (slots) and compared with a decision threshold. Integrals exceeding the threshold were declared as detected pulses, whereas those that did not exceed the threshold were declared to be non-pulse locations. Timing synchronization was hard wired from the PPM modulator to

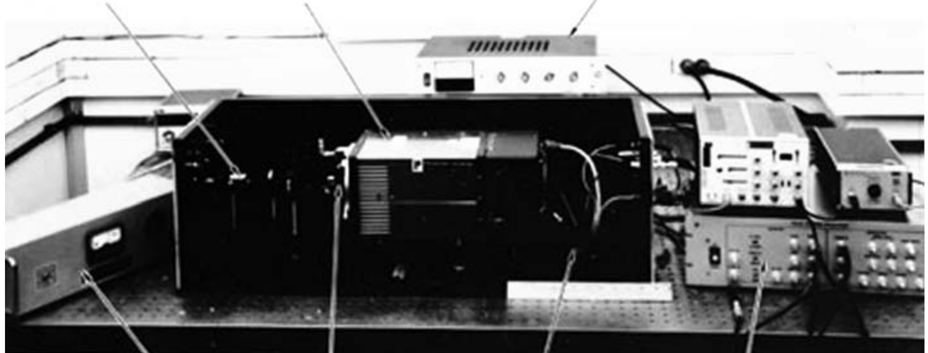


Fig. 1-3. Photograph of the 2.5 bit/detected photon demonstration.

the detector circuit so that timing errors were eliminated from the demonstration. The RS code and associated decoder were not implemented in hardware but were simulated on a computer. Data from the PPM detection process were fed into the computer. Since these data represented hard slot decisions within each PPM word, the performance that an actual RS decoder would have provided could be easily calculated. The resulting measurements demonstrated that reasonable error rates (below 10^{-6}) could be achieved at signaling efficiencies up to 3 bits/detected photon [3–9]. This demonstrated clearly that the classical "quantum limit" did not apply for this channel. There was some concern that it might be difficult to establish timing synchronization for such a link. A subsequent demonstration effort showed that the hard-wired synchronization assumption could be eliminated, at least for signals represented in this demonstration [10,11].

The interest generated by [2], and the resulting multi-bit/photon demonstration, sparked a flurry of theoretical studies to better understand the optical channel and the techniques that could be used to exploit it [12–15]. These studies considered channel capacities and computational cut-off rates for the optical channels [16–23], optimal modulations for achieving higher energy efficiencies [24–27], and codes that were well matched to those modulations [28–30]. But two things were becoming very clear. The first was that the complexity of the systems required to exceed approximately 3 bits/detected photon would increase rapidly. Indeed, Butman, Katz, and Lesh [31,32] showed that the uncertainty principle alone would limit systems to below 20 bits/photon, and that practical timing limits would hold that number even lower. Furthermore, McEliece, Rodemich, and Rubin [33] showed that, based on computational cut-off rate arguments, it would be very difficult to exceed 10 bits/photon. The second realization was that the real challenges to the utilization of optical communications were not in squeezing more out of the modulation and coding efficiencies, but in the sizes, weights, powers, and reliabilities of many of the required optical-communication component and subsystem technologies. As a result, JPL research efforts were diverted away from the information-theoretical aspects of the field and were concentrated on those key component and subsystem technologies.

1.3 Component/Subsystem Technologies

An optical-communication system requires many component technologies. Virtually any one of them can be critical depending on the specific system requirements. It would be impractical to describe them all here, but there are a few component technologies that frequently make the critical list, and these are described below.

1.3.1 Laser Transmitters

One of the most important component technologies involves laser transmitters. When JPL began work in optical communications, laser transmitters had limited powers (less than 100 mW), their efficiencies were very low (less than 1 percent), and they were very unreliable. Some efforts, sponsored by the United States Air Force, had developed a cavity-dumped neodymium-doped, yttrium-aluminum-garnet (Nd:YAG) laser for possible space applications (later downgraded for an airborne laser communication demonstration), but its wall-plug power efficiency was about 0.5 percent [34]). Such power conversion efficiencies were too low to be viable for deep-space missions where power generation is extremely difficult and costly. Building on research already underway at the California Institute of Technology (Caltech), JPL began doing research on monolithically integrated semiconductor laser arrays [35–39]. Semiconductor lasers were much more power efficient than conventional solid-state (e.g., Nd:YAG) lasers, but their output powers were much lower. It was thought that by combining many laser diode elements together in a phase-locked array transmitter, the power output could be increased to the requisite (1–3 W average) levels, and the resulting transmitters would be extremely efficient (perhaps 40 percent). Additionally, one could also consider electronic beam steering of the beam from a laser diode array.

Initial progress, both at JPL/Caltech and elsewhere, was very promising, and significant increases in power levels were achieved [40]. Additionally, phase steering was demonstrated in many devices [41,42], but two problems remained. First, despite the increases in average power levels, the PPM modulation required that the laser energy be concentrated in high peak pulses. When the full average power levels of semiconductor laser arrays were concentrated into short-duration pulses, the instantaneous power densities at the laser facets far exceeded the device damage thresholds. Additionally, high-power laser arrays required efficient thermal conduction from the lasing epitaxial layer and hence required wafer-side mounting to the copper heat sinks. But, access to that same wafer side was required to control injection currents to accomplish electronic beam steering. Hence, the mounting required for high-power generation would short out all the control signal lines for the electronic beam steering.

The semiconductor laser arrays really functioned like efficient optical batteries (i.e., efficient converters of electrical energy to continuous wave (CW) optical energy). What was needed was the equivalent of an optical capacitor that could store and accumulate that optical energy until it was needed for a short optical (PPM) pulse. Nd:YAG laser rods could act as an optical capacitor, storing the optical energy in the fluorescent lifetime of the Nd ions, but they were just too inefficient in converting electrical energy into excited Nd ions.

In 1984, Don Sipes had an idea to improve this energy efficiency [43]. He noted that the contemporary designs of Nd:YAG lasers surrounded the Nd-doped YAG rod with laser diode pumps, but stimulated Nd:YAG laser emission along the central axis of the laser rod. Furthermore, the rod material was highly absorbent at the pump laser wavelength (by design), giving rise to very high excitation levels near the circumference of the rod, but the pump power density in the region of the rod where lasing occurred was much lower. He then reasoned that if he could inject the diode laser pump energy along the same axial space where the laser cavity mirrors were stimulating the Nd:YAG laser emission, then the conversion factor would be much better. This could be done with proper anti-reflection coatings on the cavity mirrors. Additionally, if both the pumping mode and the lasing modes were made very small in diameter inside the rod, then the conversion factor would be even larger. With a research investment of only a few thousand dollars, he assembled such a laser that produced greater than 5 percent electrical conversion efficiency on the first try [43–45].

Further improvements on this approach over the years have increased the power levels to more than 10 W [46–48]. Figure 1-4 shows a later version of this design that produced 2 W of pulsed and frequency-doubled (green, 532-nm) output laser power, and up to 11 W of pulsed laser power at the Nd:YAG fundamental wavelength of 1064 nm. This design demonstrated that laser powers and efficiencies realistic for deep-space optical communication were possible. This laser structure was the only viable deep-space laser approach for almost 15 years until fiber-amplified lasers began to emerge.

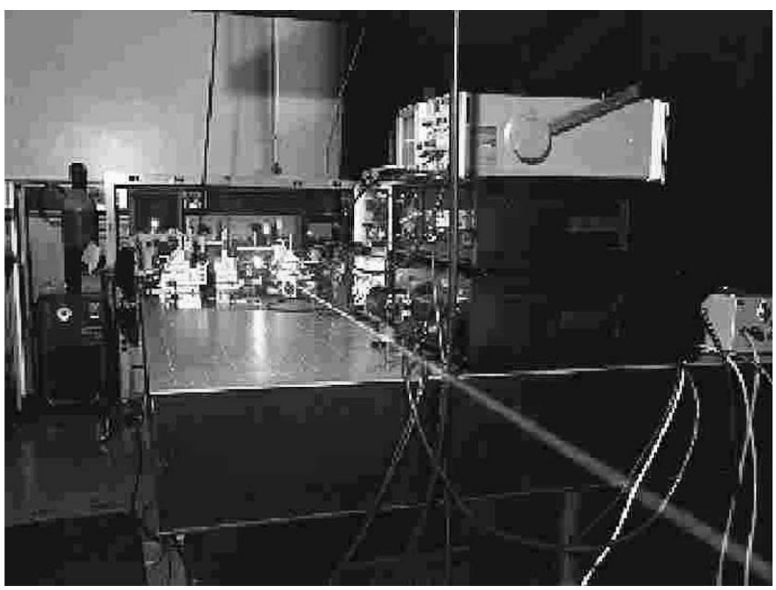


Fig. 1-4. 2-W frequency-doubled laser (11 W if not doubled).

1.3.2 Spacecraft Telescopes

Another key technology component is a thermally stable and lightweight optical spacecraft telescope. Serving as the optical version of an antenna, this telescope was required to keep surface deformations under a small fraction of an optical wavelength (a small fraction of a micrometer [μm]) and to do so over a large temperature range. Thermally stable glasses had been used in many applications, but they required too much mass. Through a Small Business Innovative Research (SBIR) contract with SSG Inc., a 30-cm-diameter telescope that was very precise and thermally stable was developed. Made entirely of silicon carbide, the telescope had a mass of only 6 kg. Figure 1-5 shows the delivered telescope.

1.3.3 Acquisition, Tracking, and Pointing

As mentioned above, one of the most important reasons for considering optical communications is the narrow beam divergence that allows the transmitted power to be concentrated on the receiving target location. However, that narrow divergence benefit comes with the penalty that the beam must be precisely pointed, or the entire benefit is lost. This pointing must be accomplished in the presence of attitude changes of the host spacecraft that are perhaps a thousand times larger than the laser beam divergence. Additionally, platform jitter disturbances can be many beam-widths in magnitude and can have characteristic frequencies of a hundred or more hertz. Finally, the transmitted beam from a spacecraft must be offset (pointed ahead) from the apparent location of the receiving target to compensate for cross velocities between the host spacecraft and the reception location. The normal way of accomplishing all these functions is for the spacecraft terminal to acquire and track an uplink beacon signal from the intended receiving target. That beacon is

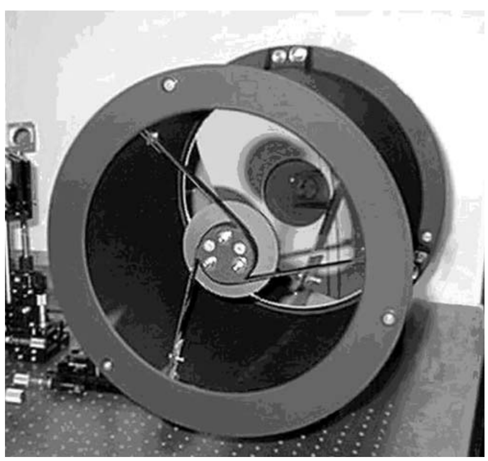


Fig. 1-5. 30-cm silicon carbide telescope.

used to precisely calibrate the attitude orientation of the spacecraft’s transmitting aperture. The beacon signal is also used to measure the vibrational components of the host spacecraft. Correction of both the telescope line-of-sight error, as well as compensation for vibrational disturbances, is then accomplished using one or more fine-steering mirrors in the optical path to the telescope. This compensation scheme can also be used to implement the needed point-ahead angle calculated from mission trajectory and planetary orbital predictions.

Initial work at JPL in the late 1980s resulted in the development of an Integrated Optical Communications Test Bed (IOCTB) shown in Fig. 1-6. The IOCTB contained the necessary components to simulate a beacon signal and accomplish the required beam-pointing functions. It served as a familiarization test bed until newer acquisition, tracking, and pointing techniques were developed.

One of the early concerns was the difficulty of getting a sufficiently strong laser beacon signal out to a spacecraft when it is at one of the outer planets. As an alternate approach, techniques were investigated that relied on the solar-illuminated Earth itself as a beacon. Several strategies have been investigated over the years that use different tracking reference sources, either from visible sunlight reflected off the Earth or from the infrared emissions of the Earth as seen against the cold sky background [49,50]. To date, while promising, these techniques have yet to prove that they can provide adequate reference signals under all the various conditions and still be competitive with direct beacon tracking.

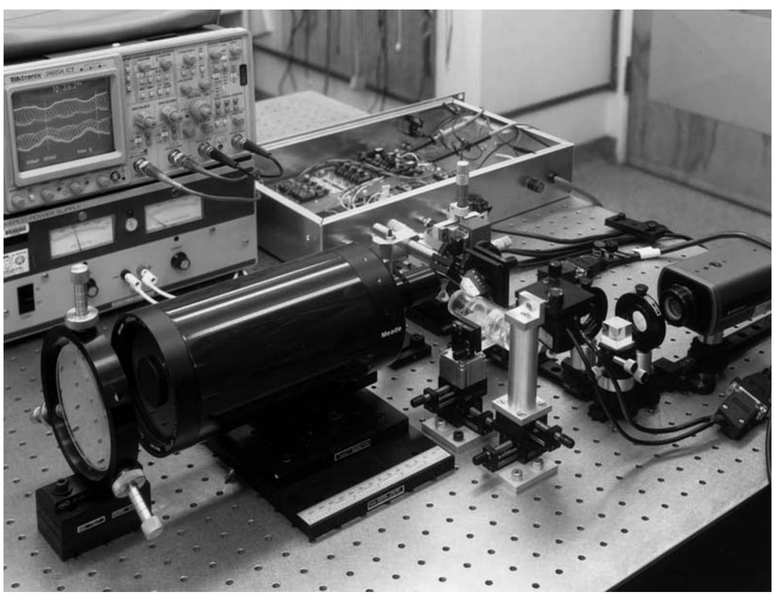


Fig. 1-6. Integrated optical communications test bed.

JPL has also investigated, as a hybrid technique, tracking of a weak uplink laser beacon signal used in conjunction with inertial sensors (e.g., accelerometers) to measure the vibrational components of the spacecraft. This approach is much more promising and allows the weak uplink beacon to be integrated longer to determine the spacecraft absolute attitude, while the inertial sensors permit compensation for the higher-frequency vibrational components [51,53,54].

1.3.4 Detectors

Another crucial component technology is that of detectors. Both detectors for optical-communication data extraction and detector arrays for spatial acquisition and tracking are needed. For data channel detection, the detector used in the multi-bit/photon demonstration was an RCA 31034C PMT. However, this and similar PMTs suffered from two problems. First, their quantum efficiencies at the primary candidate operational wavelengths were too low (typically less than 1 percent). Second, the tubes had such high gains that nominal background and/or strong signal levels would likely cause output currents that exceeded the anode plate current limitations. Clearly some other kind of detector was needed. An alternative is to use an avalanche photodiode detector (APD). Normally, APDs are operated in a mode where a bias voltage up to, but not exceeding, the spontaneous avalanche breakdown voltage is applied. The higher the voltage, the higher the gain, but also the higher the rate of spontaneous dark-count-generated detection events. Furthermore, the output resulting from the avalanche gain of the detected signal had a high variance, resulting from random multiplication gains through the photodiode's lattice structure. Although often higher in quantum efficiency, such detectors were not suited for detection of single photons.

In 1985, JPL began looking at APDs that were biased beyond the avalanche breakdown voltage. In this case, the gains would be high enough to detect single photon arrival events. Under normal conditions this would result in a constant avalanche condition due to thermally generated carriers in the photodiode. However, by cooling the APD nominally down to about liquid-nitrogen temperatures, the thermal carrier generation process could be significantly suppressed. That would leave the photodiode detector ready to trigger a massive avalanche, but with most of the thermally generated false detections eliminated. The result would be an optical detector that operated similarly to the way a Geiger counter works on radioactive detection events. To verify this, a test setup was created, and APD detectors were tested under single-photon input level conditions. Greater than 30 percent quantum efficient detection of single photons was demonstrated [55–60].

One of the problems identified in these "Geiger-mode" detectors was that after a triggered event occurred, whether from an incident signal or background photon, or from a residual thermally generated carrier, the avalanche process would have to be stopped (or quenched). One way to quench these avalanches was to place a resistor in series with the APD. When an avalanche would start, the voltage drop across the resistor would reduce the voltage across the APD to below the avalanche breakdown voltage, thus stopping the avalanche. However, the resistance of the load resistor, coupled with the junction capacitance of the APD, resulted in a relatively large resistance–capacitance (R–C) time constant, thus overly limiting the bandwidth of the detection system. An alternate approach was to build an active quenching circuit that would rapidly trigger an electronic voltage interrupt. Unfortunately, such circuits were difficult to design and operate at that time.

More recently, work has been done on operating commercially available APDs at voltages just under the avalanche breakdown voltage. Since the voltage is high, the gain, and hence detectivity, is also high. But, since the detector is operated below avalanche breakdown, the detector does not lock up in a sustained avalanche, and the output resembles an amplified version of the input. Additionally, by cooling the detector, the resulting dark count rates can be minimized. Single-photon detection efficiencies greater than 30 percent have been demonstrated [61].

The other major detector needed is a detector array for the spatial acquisition and tracking system on the spacecraft. This detector is used to track the location of a beacon signal from the intended receiving location and often a portion of the outgoing transmit beam signal for precision beam pointing. The detector must have a large-enough field of view to cover the attitude uncertainty of the host spacecraft (often several milliradians [mrad]), yet produce final spatial resolution measurements that are a small fraction of a transmitted beamwidth (resolutions well below a μrad). Furthermore, the detector must be read out fast enough to compensate for higher-frequency vibrations on the spacecraft that would cause excessive beam jitter. Conventional charge-coupled device (CCD) detector arrays have adequate field of view (FOV) and resolution, but the typical frame rates (10–30 Hz) are inadequate to follow higher-frequency jitter components. A significant amount of effort was then directed toward windowed CCD arrays. With a windowed array, only small regions (typically 10 × 10) around the desired spatial tracking points need to be read out; after which, the rest of the array signal can be dumped and the next image taken. By windowing, the repeat time to the desired tracking points (after acquisition has occurred) can be fast enough to track even the higher-frequency jitter components. In the future, even more efficient tracking detectors will be possible with the use of active pixel sensor (APS) detector arrays. With APS detectors, the signals from the windowed regions of interest will not need to be read off the detector chip. Instead, it will be possible to process the signals into real tracking information via on-chip complementary metal oxide semiconductor (CMOS) processing.

1.3.5 Filters

On the receiving end of the link, narrow-band filters will be required before the detectors, especially if daytime reception on the ground is to be used [62]. Narrow transmission bandwidths will eliminate much of the background light interference, but the throughput efficiencies must be high to avoid causing significant loss to the desired signal. Multi-dielectric filters are the commonly used filters, but they are limited in how spectrally selective they can be and still have adequate throughput.

One filter investigated in this category is the Fraunhofer filter [63]. In the solar spectrum, there are narrow regions where the solar energy is trapped by certain elements in the Sun’s photosphere. These are regions of the solar spectrum where the Sun is effectively dark (or at least not so bright). By selecting a laser line that corresponds to a Fraunhofer line, and then using an interference filter matched to that line, communications can take place with significantly lower background interference levels. One of the laser wavelengths of early interest was that of a frequency-doubled Nd:YAG laser at 532 nm. Several spectral dips exist in the solar spectrum near 532 nm.

To achieve really narrow passbands (less than 1 nm) it is necessary to use filters that are based on atomic transitions in materials. Atomic resonance filters (ARFs) can produce sub-nanometer bandwidths. However, these filters cannot be used in front of acquisition and tracking systems since the filtering operation relies on the absorption of a photon at one wavelength and the corresponding emission of another at a new wavelength. The creation of the new photon is dependent on the energy absorption of the input photon, but its angular direction is not preserved. To get around this, work was done in the early 1990s on the development of filters that produced polarization rotations as a result of the anomalous dispersion shifts of certain pumped gasses. Two versions were studied: the Faraday anomalous dispersion optical filter (FADOF) and the Stark-shifter anomalous dispersion optical filter (SADOF) [64,65]. Both filters work by passing polarized light into an atomic cell. If the input light is precisely on resonance with the excited gas in the cell, the input light will undergo a polarization rotation due to the anomalous dispersion of the gas. Light that is not precisely on resonance (i.e., background light) will pass though the cell but without the polarization rotation. By placing a crossed polarizer at the output of the cell, only the on-resonance light is allowed to pass. Furthermore, since the light is not absorbed and then re-emitted, the angular direction of the on-resonance light is preserved. A diagram of the SADOF filter is shown in Fig. 1-7.

1.3.6 Error Correction Coding

The last, but by no means the least, component technology to be discussed is optical coding. As mentioned earlier, the original multi-bit/detected-photon

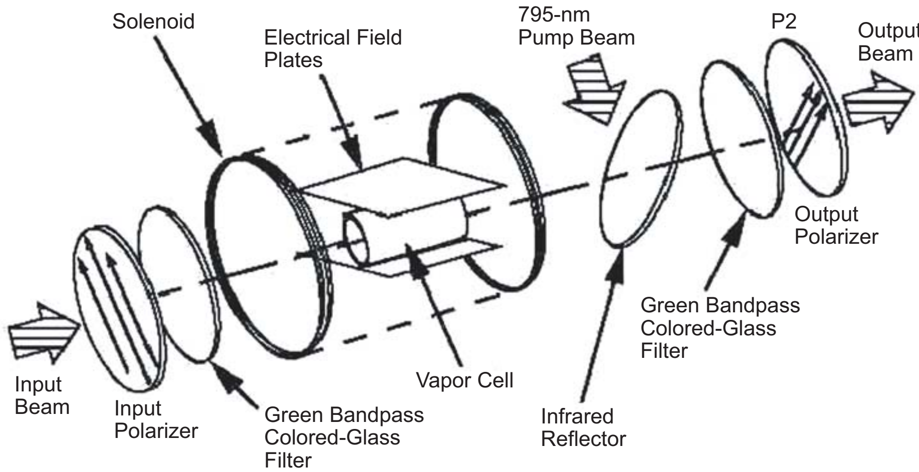


Fig. 1-7. Optical path through a SADOF filter.

demonstration used high-order PPM modulation (256-PPM) with a high alphabet (8-bit alphabet) RS code. The RS alphabet was matched to the PPM modulation since each 8-bit character would specify which of the 256 pulse locations would be used for that character. The prevailing belief was that the higher the order of the PPM modulation, the better the performance, provided the modulation was used with a matching-alphabet RS code. However, as the PPM order increased, the matching RS alphabet (and hence code) became much more complex. Furthermore, it was known that if the PPM order was reduced (along with its matching RS code), performance of the link was significantly reduced. This usually forced system designers to consider only high-order PPM modulations, but high-order PPM meant a high value of peak-to-average power level from the laser since the laser's average power was concentrated in a much narrower (and infrequently filled) pulse slot. Laser power limitations became a constraint on how high the order of the modulation could be.

Recent progress has been made in the development of codes that can relax the need for higher-PPM formats, and hence the required peak-to-average power levels of the lasers [66–70]. The codes (called accumulator codes) are based on product-coding techniques where simpler codes are combined and then jointly (and iteratively) decoded. One of the benefits is that one can start with a lower-PPM alphabet that is further from the overall channel capacity limit and regain a large portion of the lost performance with coding. Going to higher-order PPM modulations and using a good code over that modulation is still better in terms of performance, but the difference between properly coded lower-order modulations and properly coded higher-order modulations has diminished. Table 1-1 gives a comparison of several different PPM modulation orders and corresponding coding gains from the accumulator codes. Note the higher coding gains for the lower PPM orders.

Table 1-1. Coding gains of accumulator codes (in dB) for various PPM modulations.

PPM Order	2048	256	16	4
Gain relative to RS code	2.25	2.78	4.82	9.08
SNR gap to capacity (dB)	1.26	1.29	1.03	1.08
Optimal constraint length	2	2	3	4
Average iterations required	9	9	7	6

1.4 Flight Terminal Developments

Component technologies by themselves will not constitute an overall subsystem. They cannot be just hooked together and used because the design parameter spaces are large and the interfacing requirements can be tight. Furthermore, even the mounting platform (e.g., optical bench) on which some of the optical components are mounted must often be both thermally and mechanically stable since the design tolerances, due to the short wavelengths of optical signals, are frequently very tight and must be maintained over the temporal and environmental life of the system. Several flight transceiver (terminal) designs have been completed over the last two decades.

1.4.1 Optical Transceiver Package (OPTRANSPAC)

The first flight terminal system design was the Optical Transceiver Package (OPTRANSPAC) study conducted it 1984 [71]. It was a contracted study with McDonnell Douglas Corporation and leveraged their prior work for the United States Air Force on the Airborne Flight Test System and subsequent development activities for the Defense Support Program's (DSP's) planned Laser Crosslink System (LCS). The design had independent detectors for spatial acquisition, spatial tracking, and uplink data detection. The design was being performed as a pre-project study for a possible flight demonstration on the Cassini deep-space mission to Saturn. The OPTRANSPAC system design had a 28-cm telescope, had a 400-mW (frequency-doubled Nd:YAG) laser, and would return a 100-kbps communication flow from Saturn to a 10-m-diameter Earth-orbiting receiving aperture. The mass and power consumption estimates were 52 kg and 57 W, respectively, and the terminal occupied a volume of approximately 0.1 m^3. At the time, the mass was considered too much for the Cassini mission to fly as a mission-enhancement demonstration, so the full-scale development was not continued. However, the OPTRANSPAC study results were used as a basis for the IOCTB development mentioned earlier. A sketch of the OPTRANSPAC terminal design is shown in Fig. 1-8.

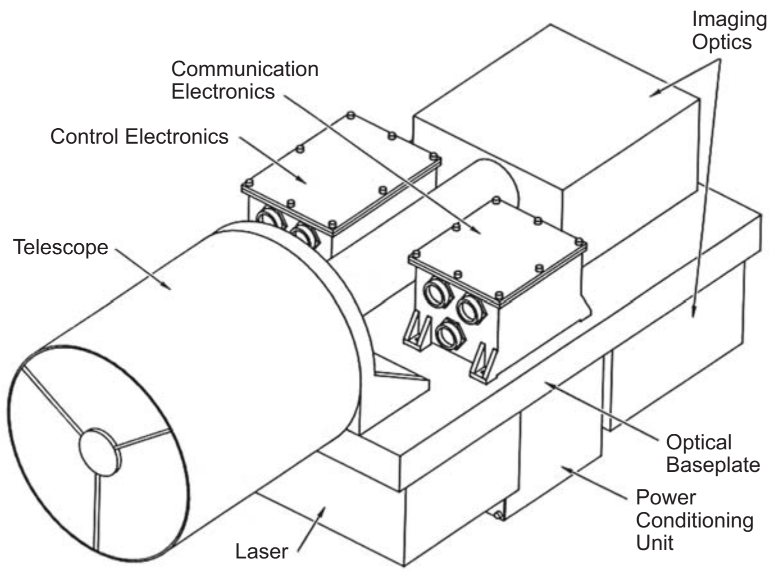


Fig. 1-8. Isometric drawing of the OPTRANSPAC flight terminal design.

1.4.2 Optical Communications Demonstrator (OCD)

One of the attributes of the OPTRANSPAC design was that it used separate detectors for acquisition, for tracking, and for beam point-ahead (the offset angle needed to lead the Earth-station receiver when there is relative cross-velocity between the two ends of the link). Additionally, there were separate fine-steering mirrors to implement the necessary beam centering and offset functions. Detectors and steering mirrors are primary optical system components, but they usually need secondary elements (e.g., focusing lenses and beam-folding mirrors) to make them work properly. All these components must be precisely held on thermally stable structures in space terminals. This meant that if the basic design of a flight terminal had a lot of primary components, then the overall complexity, mass, and cost of the terminal would be much higher due to all the elements (primary components, secondary components, and supporting infrastructure) required to make the end system function properly. By realizing this relationship, it was conversely realized that if the number of primary components could be reduced, then the number of secondary components would also be decreased, as would the requirements for the supporting structure. This realization led to the basic design of the Optical Communications Demonstrator (OCD) [72–76].

The fundamental design for the OCD is shown in Fig. 1-9. The OCD concept works as follows. A beacon signal is sent to the flight terminal from the intended receiving terminal. That signal is received on the flight terminal by its telescope (depicted by just a lens in the diagram for simplicity). The telescope

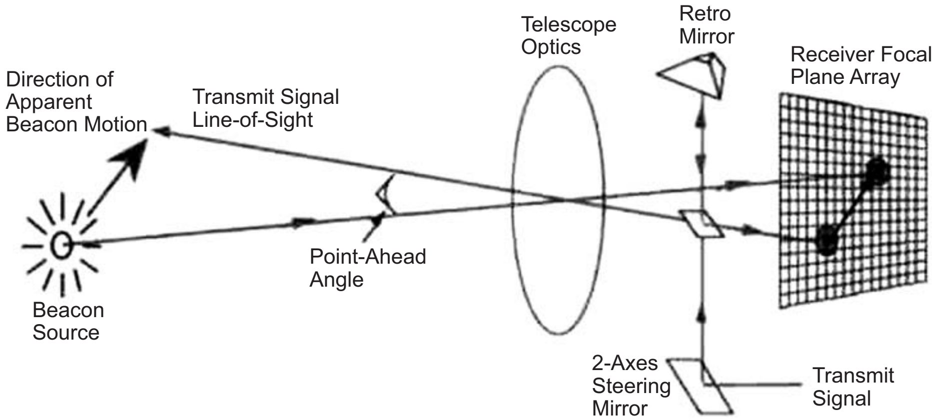


Fig. 1-9. Concept diagram for the Optical Communications Demonstrator (OCD).

collects the beacon signal and focuses it to a point on the receiver focal-plane array in the terminal. The location of this spot on the array represents the direction from the received beacon signal relative to the telescope's axis (the center of the array). The array size determines the field of view of the telescope and is large enough to cover the initial pointing uncertainties of the telescope (often defined by the attitude control dead-band limit cycle of the spacecraft). No overt effort is made to center the received beacon signal on the focal-plane array. This just represents the knowledge of the direction to the receiver. The modulated laser signal that is to be returned by the flight terminal to the ground receiver is coupled (via optical fiber) into the OCD assembly and initially strikes a two-axis steering mirror. After reflecting off the steering mirror, it passes up to a dichroic beam splitter that reflects almost all the signal out of the telescope. However, there is a small amount of signal that passes through the dichroic beam-splitter and progresses upward to a retro-reflector. The retro-reflected signal returns to the backside of the beam-splitter where it is directed toward and focused onto the focal-plane array. This spot location represents the direction of the outgoing laser signal relative also to the telescope axis. The vector difference between the focused beacon signal and the focused residual of the laser transmit signal on the focal plane represents the angular difference between the received and transmitted directions and is independent of the axis of the telescope. (The actual axis of the telescope is common and drops out in the vector difference.) Now, as stated earlier, there is a need to implement a point-ahead angle to the transmitted beam. This can be done by simply monitoring the vector difference between the two focused spots and making sure that it represents the needed point-ahead angle (which can be easily calculated given the orbital predicts and the nominal spacecraft-orientation information.

Note that in the OCD design there is only a single focal-plane detector array and a single two-axis steering mirror (primary components). Since the number of primary components has been reduced, there will be a corresponding reduction in the number of secondary components (not all are shown), and hence, there is a simplification of the entire structure. This design is called a minimum-complexity design, and it was specifically invented to decrease the complexity, mass, and cost of the flight design.

The OCD was implemented in a laboratory-qualified form/fit/function realization based on this minimum complexity design. Figure 1-10 shows the resulting implementation. The terminal has a 10-cm-diameter telescope, and the entire unit is about the size of a loaf of bread. The basic design assumes that the OCD is body-mounted to the spacecraft and that coarse pointing of the terminal is accomplished by the attitude orientation of the spacecraft. This is realistic for many deep-space missions, and in fact, the same is usually done with the conventional RF antennas. In those cases where pointing independent of the spacecraft orientation is required, such as is more common with Earth-orbital missions, then the OCD terminal can be mounted on a separate two-axis gimbal or used in conjunction with an external two-axis controlled-steering flat mirror. Figure 1-11 shows the OCD on a two-axis gimbal. Although the OCD was designed as a laboratory-qualified terminal, it has been used as the basis for many proposed flight designs. The basic terminal design would allow kilobits per second data returns from Pluto distances and multiple gigabits per second data returns (with significant excess link margins) from Earth-orbital distances to the ground. Additionally, the OCD terminal has also been taken into the field for a series of 46-km mountain-peak-to-mountain-peak demonstrations (see Section 1.10.4).

1.4.3 Lasercom Test and Evaluation Station (LTES)

The characteristics of a flight terminal engineering model cannot be evaluated without also developing a test infrastructure for measuring its

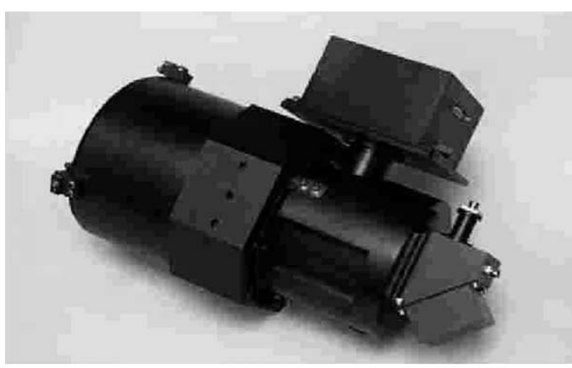


Fig. 1-10. Basic OCD unit.

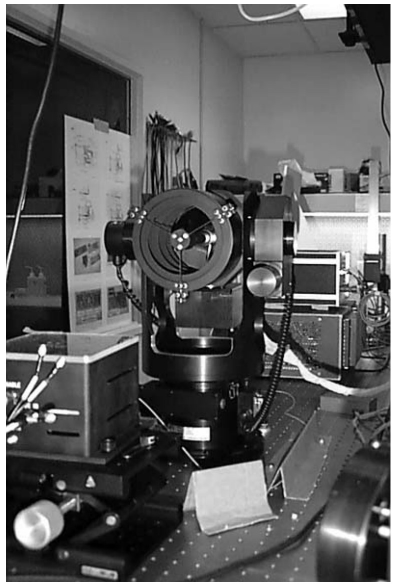


Fig. 1-11. OCD on gimbal.

performance. Accordingly, the Lasercom Test and Evaluation Station (LTES) was developed. The LTES was viewed as a more general-purpose test station, so it was required to operate over a broad wavelength band (from 0.5 μm to 2.0 μm). The LTES can provide a calibrated beacon signal for use with the flight-engineering model under test, and it can receive and analyze the laser signal from that engineering model. Tests that can be made include spatial acquisition and tracking performance parameters, detection of transmitted data, and measurement of transmitted power levels. Although designed originally as a test infrastructure for the OCD, the LTES was first used to perform selected tests on a Ballistic Missile Defense Organization-developed optical communications flight terminal that flew on the Space Technology Research Vehicle 2 (STRV-2) mission. The LTES was sensitive enough to determine that the flight unit would have significant beam wander and misalignment of the parallel transmitting lasers as a function of the terminal warm-up temperature. Figure 1-12 is a photograph of the LTES.

1.4.4 X2000 Flight Terminal

The next major flight terminal design effort was undertaken as part of the X2000 program. The X2000 program was initiated to fill the gap of major needed technology developments required for future missions. It was recognized that because of the NASA shift to faster-better-cheaper (FBC) missions, the technology developments that had customarily been developed as part of the former "flagship" missions would no longer be possible.

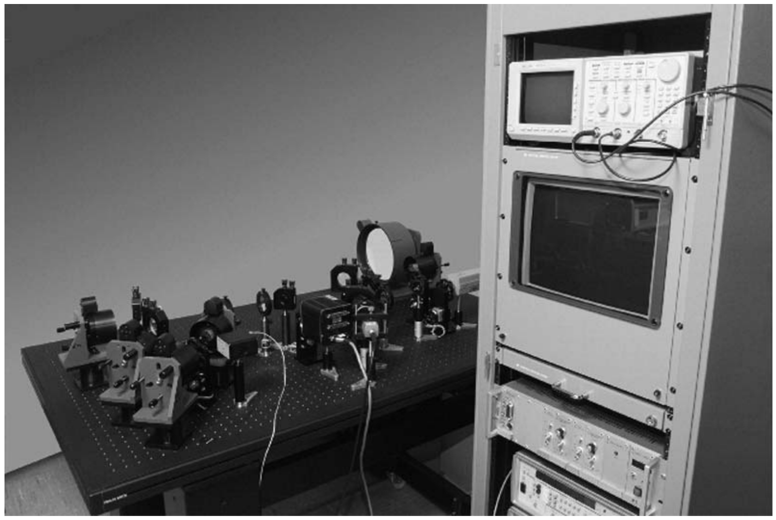
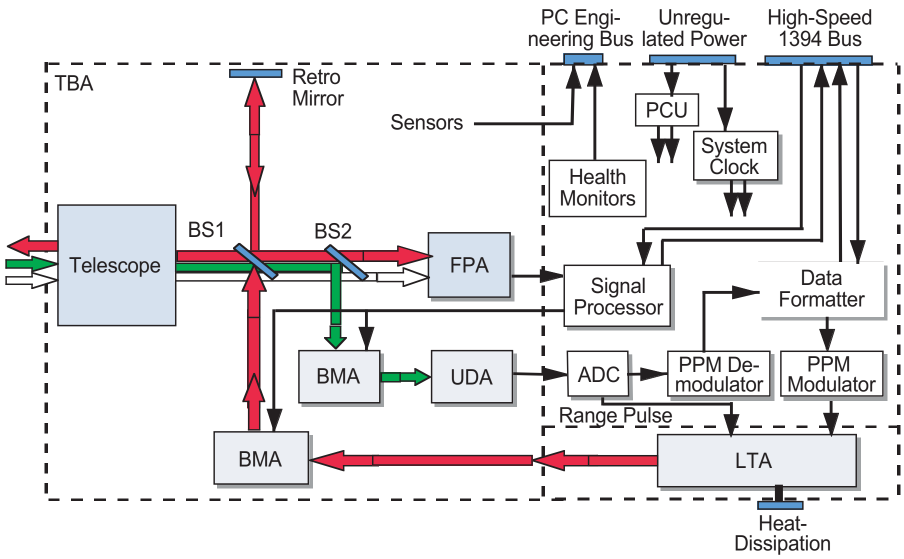


Fig. 1-12. Photograph of the LTES.

Development of an optical communications flight-qualified engineering model terminal for a proposed Europa Orbiter mission was the second largest planned development in the program.

A block diagram of the design is shown in Fig. 1-13, and it had several features that had not been included in the OCD development. First, the diameter of the telescope was increased to 30 cm. This was based on the successful development of the silicon carbide telescope mentioned earlier. Second, it was realized that the basic structure of the OCD contained a telescope and a focal-plane array, the two primary components in an imaging camera. Third, an uplink command detector path was added. Since this detector was a high-speed detector, it could also serve as an uplink ranging detector for an optical turn-around ranging system. Thus, the requirements for the X2000 design included dual-use as a science imaging camera and as an uplink reception capability for command and ranging. Furthermore, the proposed Europa Orbiter mission study team was considering the use of a laser altimeter. It was realized that the optical communication telescope and high-speed uplink detector could also be used as the laser altimeter return signal receiver/detector. A computer-aided design (CAD) drawing of the X2000 terminal preliminary design is shown in Fig. 1-14.

The X2000 optical communications development proceeded to the point of a concept design. However, budget pressures in the rest of the X2000 program ultimately caused cancellation of all X2000 developments except for the primary element, a spacecraft computer/avionics system. The optical communications terminal design had been progressing well, but the application time frame for the technology was considered to be far enough to accommodate



ADC = Analog-to-Digital Converter
BMA = Bi-Axis Mirror Assembly
FPA = Focal Plane Array
LTA = Laser Transmitter Assembly
PCU = Power Conditioning Unit
PPM = Pulse Position Modulation
TBA = Telescope & Beam-Optics Assembly
UDA = Uplink Detector Assembly

Fig. 1-13. Architectural design of the X2000 flight terminal.

the delayed development. The system and analysis to that date were captured in a study report [77].

1.4.5 International Space Station Flight Terminal

Another flight development program came along a few years later. In 1996, a NASA call was released for payloads that could be demonstrated on the International Space Station (ISS). The objective was to use the ISS as an engineering center for such demonstrations. A proposal was written, and in 1997 the proposal was selected for development. The program was funded under the ISS Engineering Research and Technology (ISSERT) program that also funded a number of other attached payload developments. The terminal design was based on the OCD architecture, and the plan was to transmit at least 2.5 Gbps from a terminal mounted on the ISS external nadir-pointing truss to the ground. The flight terminal would be developed and integrated with the ISS express pallet, for subsequent transport in the Space Transportation System (STS or Space Shuttle) to the ISS. The ground terminal would be a new Optical Communications Telescope Laboratory (OCTL) that was already funded under the Deep Space Mission System (DSMS) Technology Program (see Section 1.12.1). The operational concept included an uplink beacon from OCTL to the ISS mounted terminal. The flight terminal would spatially lock onto that beacon

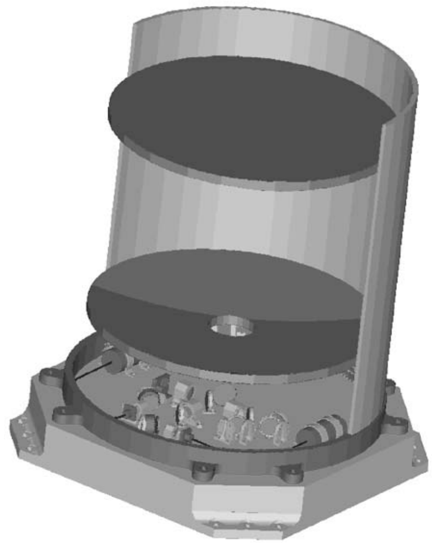


Fig. 1-14. CAD drawing of the X2000 flight terminal design.

and transmit down a pseudo-random coded data stream. Early in the program development, the ISSERT management at NASA Johnson Space Center realized that the optical communication terminal represented a valuable resource that would likely be underutilized. As a result, they initiated a change order to provide an optical-fiber transfer line from the interior of the ISS to the optical communication terminal location on the external truss. This would allow real data to be sent over the optical link to the ground.

Figure 1-15 shows the location on the ISS external truss where the terminal was to be located. Unfortunately, as was the case in the X2000 development, budget pressures were heavy here as well. The program progressed through Phase A and had just completed its preliminary design review (PDR) when budget pressures related to the building of the core ISS resulted in cancellation of all attached payload developments, including the optical communication terminal.

1.5 Reception System and Network Studies

Studies and system designs have also been done on the Earth-reception side of deep-space optical communications links. Both ground-based and Earth-orbital receivers have been studied, although the ground-based receivers appear to be the most realistic for the time being. However, that may change over time if access to space becomes more routine and less costly.

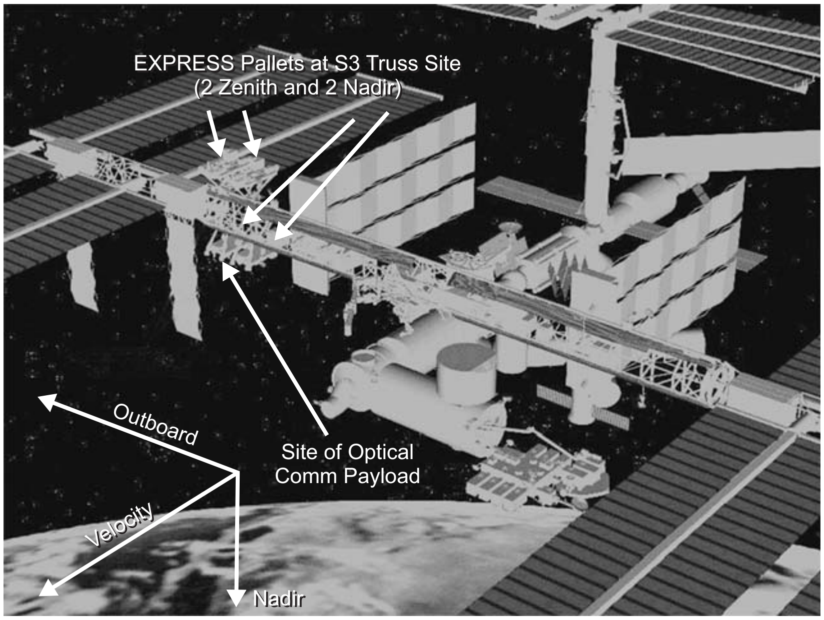


Fig.1-15. ISS showing planned site for the optical communication terminal.

1.5.1 Ground Telescope Cost Model

The first serious look at the definition of a ground receiving system was done in 1986 and involved establishing a cost-versus-performance model for ground-based telescopes [78,79]. The study started with a set of data on existing RF, solar concentrator, and optical astronomical telescopes. When the costs of those telescopes were plotted as a function of diameter, it was noticed that the costs could be modeled as

$$C = \alpha D^x$$

where C was the cost (in \$M), D was the diameter of the telescope (in meters), and x was a value that varied between 2.4 and 2.8 (taking 2.6 as a nominal value). The value of α was dependent on the inverse of the telescope's focused blur circle diameter "F" and was approximately given by

$$\alpha = 10^5 / F$$

(the actual expression is given in [78]). Next, the performance of a communication link was calculated as a function of telescope diameter and blur circle using a reference transmitter and a set of background conditions. Since the cost and the performance could each be calculated based on the same two parameters (diameter and blur circle), then the cost of the telescope could be plotted as a function of communication performance with telescope diameter and blur circle diameter as parameters. Upon optimizing over diameter and blur circle, one then had a plot of optimized-cost-versus-communications performance.

Figure 1-16 shows the results of this analysis but extrapolated to a worldwide network. The analysis showed that the knee of the cost curve occurred at about 18 dB of improvement over the reference X-band link. The values of the optimized parameters in this region were a 10-m-diameter telescope and a blur circle that was larger (less precise) than the diffraction-limited focus. This result was intuitively satisfying since it was known that 10-m-diameter diffraction-limited telescopes could be quite expensive but that similar-sized solar concentrators were much less expensive. Since non-diffraction-limited telescopes were essentially photon buckets, then this also meant that direct detection of the received signals could be used, and there would not be a need to compensate for atmospheric turbulence-induced phase fluctuations.

1.5.2 Deep Space Optical Reception Antenna (DSORA)

Given the insight afforded by the cost-modeling effort, a series of studies was conducted to define, analyze, and estimate the cost factors for various realizations of a 10-m-diameter photon bucket [80–88]. These generally went under the name of Deep Space Optical Reception Antenna (DSORA). Early in the process, it was realized that some form of sunshade would be important if the system was to be used in the daytime, especially if that use was directed

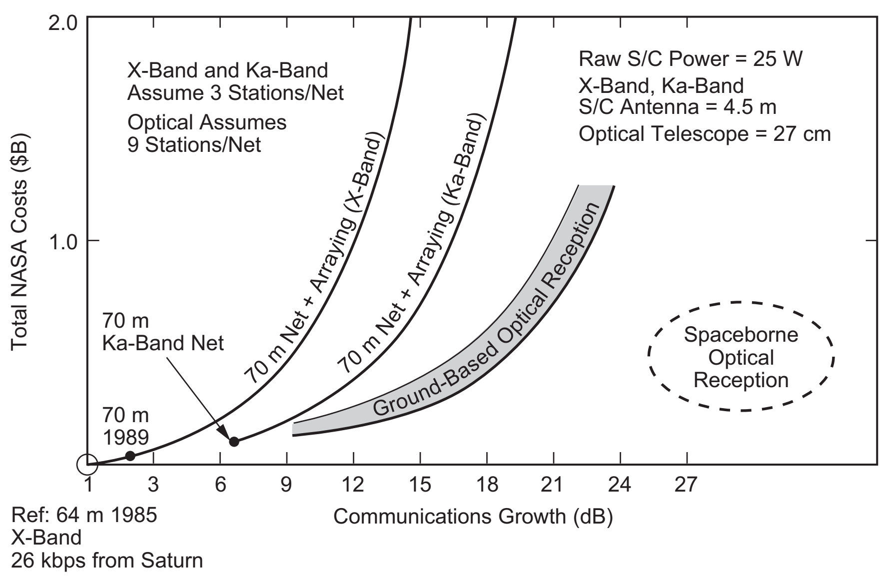


Fig. 1-16. Optimized cost model for Ka-band, X-band, and optical reception.

anywhere close to the Sun. Several sunshield concepts were explored, including the use of an external tube outside, but connected to, the dome. The favored approach was an "integral" sunshield that followed the "soda straw bundle" concept. The idea was to collect together a set of hexagonal tubes that had cross-sections the same sizes and shapes of the primary mirror segments. These would be placed over the primary collector surface, but with the lower portions of the central "tubes" shortened so that the ray paths from the primary mirror segments would not be blocked from getting to the secondary mirror. Since the length/diameter (*L*/*D*) ratio of each "tube" was large, the telescope/sunshield could point much more closely to the Sun without direct sunlight hitting the primary mirror surface. A drawing of the DSORA with an integral sunshade is shown in Fig. 1-17.

The remaining challenge, however, was the fact that the tubes became good collectors of solar radiation (heating), and there was concern that unacceptably large turbulence would result. Several concepts, including the use of "expanded metal" (similar to that used in window screens), were considered to mitigate this effect.

1.5.3 Deep Space Relay Satellite System (DSRSS) Studies

In 1992, and after examining various DSORA concepts, it was decided to look more carefully at the possibility of an orbiting reception station rather than a ground-based station. Two study contracts were let for a Deep Space Relay Satellite System (DSRSS), one to Stanford Telecommunications and the other to TRW. Actually, both studies were part of a periodic look at space-based

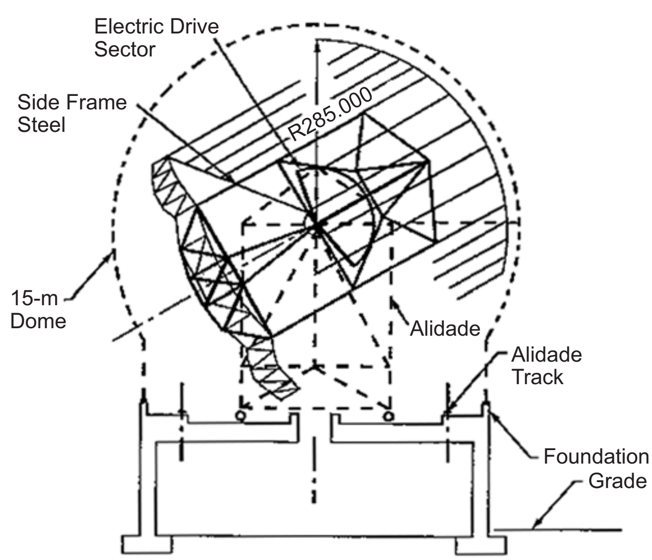


Fig. 1-17. Cross-section view of DSORA with integral sunshade.

reception for deep-space signals in general and were partially a re-examination of a concept for an orbiting RF-receiving station that had been done 14 years earlier [89]. Furthermore, the study statements of work required that the contractors look at both RF and optical reception stations to see which was the most attractive. The study contracts were for a 12-month duration, but at the mid-contract reviews, both contractors reported that the RF-reception system would not be competitive and requested that they concentrate the remainder of their efforts on the optical-system definition studies. The design proposed by Stanford Telecommunications was an on-orbit erectable optical telescope of 10 m in diameter [90]. TRW provided designs for two orbiting receivers, one a remotely deployable 10-m telescope that used direct detection, and a smaller 4-m diffraction-limited receiver that used coherent detection [91]. Based on cost and risk assessments, they did not recommend the smaller coherent system over the larger direct detection one. Although both designs would allow operation without having to worry about cloud blockages or daytime atmospheric scattered light, the cost estimates for these designs were not competitive with a network of redundant (i.e., spatially diversified to increase weather availability) ground stations. As a result, the orbital network approach was placed on the back burner for reconsideration at some time in the future, most likely as a possible second-generation capability to augment an earlier ground-reception network infrastructure.

1.5.4 Ground-Based Antenna Technology Study (GBATS)

In parallel with the DSRSS studies, JPL performed an updated study on ground-based optical receivers. The study, dubbed Ground-Based Antenna Technology Study (GBATS), considered both the details of the design for a 10-m optical reception ground station as well as the overall operational network architecture using such stations as element nodes [92]. The design of the 10-m telescope consisted of a segmented primary aperture with active control of the primary segments (to control low-bandwidth aperture distortions caused by gravity loading, thermal distortions, and wind buffeting). Furthermore, a collapsible dome structure similar to an existing United States Air Force 3.5-m telescope was included. For the network architecture, it was necessary to consider spatial-diversity reception from the beginning to circumvent cloud-cover outages.

Two fundamental architectures were considered. The first consisted of three clusters of three optical telescopes in each of the three current DSN RF antenna regions. This would allow the three-longitude paradigm of the current DSN to continue. However, for spatial diversity benefits, each of the clusters at each longitude would have to be spread out over several hundred kilometers to be in different weather cell regions. This automatically implied a network of nine stations. For the other architecture, the constraint that the stations needed to be somehow “clustered” around an existing DSN station longitude was removed. This allowed the stations to be located in a pattern where one could act as a redundant neighbor for any of the stations in its neighboring longitudes. Networks of 6, 7, and 8 stations dispersed linearly in longitude around the globe were considered. It was found that the linearly dispersed optical subnet (LDOS) approach, rather than the DSN-centric “clustered” approach, was the more cost effective. Figure 1-18 shows the basic design of an optical station from GBATS, and Fig. 1-19 shows a sample LDOS configuration taken from that study. The GBATS results were used to compare with the DSRSS study conclusions. The cost, performance, and risk comparisons clearly favored the ground-based-network approach.

1.5.5 Advanced Communications Benefits Study (ACBS)

Although a lot of interest was being generated in the area of optical communications, technologies for alternative approaches were also progressing, and it became evident that a comparison of optical communications with an upgraded X-band system, as well as the emerging Ka-band system, was

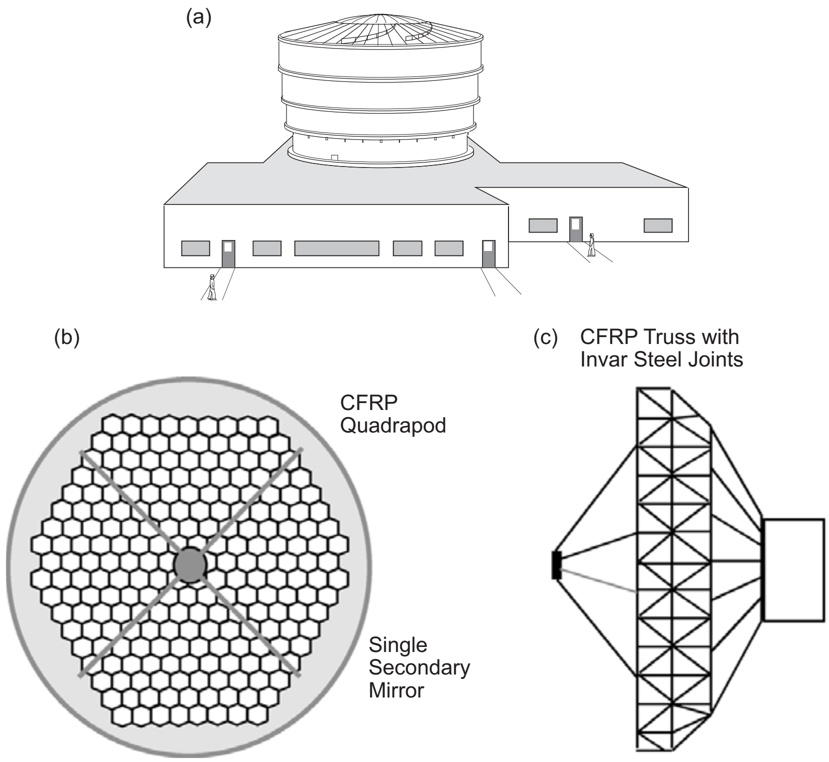


Fig. 1-18. GBATS ground station (a) building with collapsible dome; (b) single secondary mirror of carbon-fiber-reinforced plastic (CFRP); and (c) CFRP truss with invar joints.

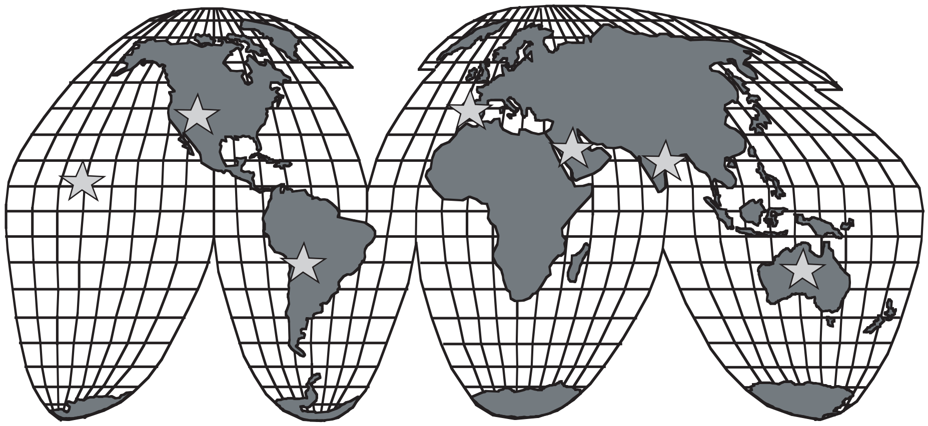


Fig. 1-19. Global map of the seven-station LDOS network.

appropriate. In 1996, an Advanced Communications Benefits Study (ACBS) was initiated [93,94]. The study constraints were to consider reception of signals from Mars at three daily data return volumes (0.1 gigabit (Gb), 1 Gb, and 10 Gb). Enhanced X-band, the emerging Ka-band, and the optical communications end-to-end systems designs were developed, and the overall cost estimates were compared. The cost estimates considered the cost of mass and power on the spacecraft, the non-recurring and recurring costs of the spacecraft terminals, and the cost of the ground infrastructure (recognizing that there was already a DSN infrastructure in place). As part of this study, a more detailed assessment of the design and the cost estimates for optical ground infrastructure were developed. The cost estimates were then evaluated based on total initial investment cost and the recurring spacecraft costs over some number of missions. Figure 1-20 shows the result of the study for the 10-Gb/day data volume design point. The results show that the initial investment required for the optical system is higher than either the X-band or the Ka-band approaches, but that investment cost is recovered after 5–8 missions because of the lower recurring costs of the optical systems.

1.5.6 Earth Orbit Optical Reception Terminal (EOORT) Study

In 1998, there was another examination of the orbiting optical reception approach. Building on the DSRSS study results, the Earth Orbit Optical Reception Terminal (EOORT) study considered two orbital configurations, one a 7-m optical photon bucket receiver and the other a 4-m coherent receiver [95]. The reasoning was that these values more closely compared in terms of performance with the 10-m ground-based designs that were being considered. Team X at JPL performed studies of these two configurations. Again it was found that the larger but noncoherent reception approach was less expensive,

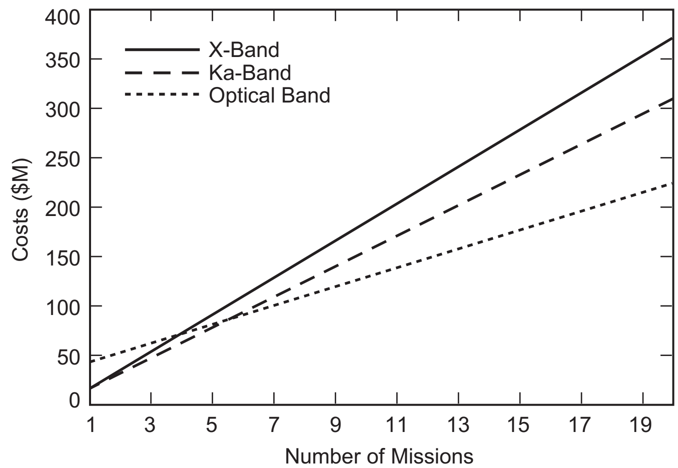


Fig. 1-20. Life-cycle cost comparisons of expanded X-band, Ka-band, and optical communications as a function of number of user missions.

but that the economic comparisons with the ground-based approach still favored the ground.

1.5.7 EOORT Hybrid Study

The real attraction of an orbiting receiver is that one does not need to worry about infrequent (but still possible) cloud-cover blockages during mission critical events. Still, for the bulk of the time, a diversified ground network provides perfectly adequate coverage and can do so at a fraction of the cost. This led to the idea that a hybrid approach might be a good solution. In 1998 a follow-on study to the EOORT study was conducted [96]. This study considered a reduced number of ground stations that could receive signals from the spacecraft much of the time (i.e., when not obscured by clouds), but it also had an orbital system with a small (70-cm in the study) telescope to guarantee that at least critical data reception could be received even when the relevant ground stations were clouded out. The solution looked attractive, although there would be a more challenging signal design required. In particular, the signal would have to be decodable with only the 70-cm aperture for the critical data, but it would provide the remainder of the science data if one or more of the ground station connections were available. How this would work operationally will require more investigation.

1.5.8 Spherical Primary Ground Telescope

One cost-effective approach for a ground receiver is to use a primary telescope aperture made up of spherical segments. Such segments are easy to fabricate, and hence, they can save significant costs for the station. However, spherical segments also cause spherical aberrations that can further blur the telescope's focused energy (and hence cause the reception system to be more susceptible to background light interference). A recent design [97–99] took such a structure and matched it with a clamshell spherical aberration corrector. This looks like a very promising way to reduce costs of the ground station without sacrificing the performance of the system. Figure 1-21 shows a sketch of the optical station. Figures 1-22 and 1-23 show the optical ray trace diagrams for the segmented spherical primary mirror and the clamshell corrector, respectively.

1.5.9 Space-Based versus Ground-Based Reception Trades

Studies have continued on the definition and associated cost estimates for ground-based reception stations as well as space-based alternatives. There are certainly advantages to being above the Earth's atmosphere for signal reception. At the same time there are many advantages to having the reception

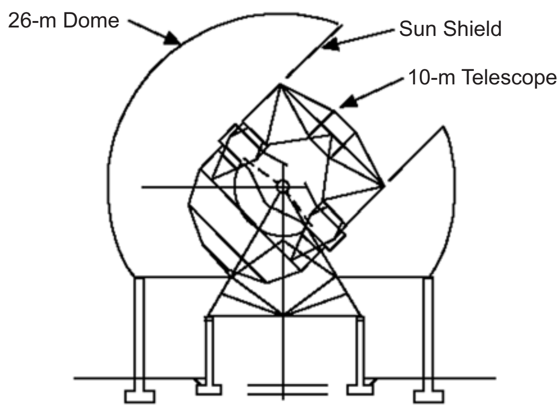


Fig. 1-21. Telescope and dome.

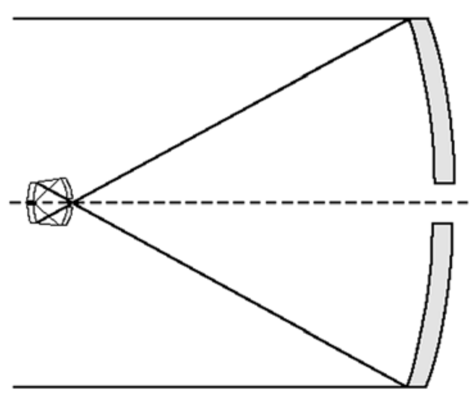


Fig. 1-22. Spherical primary/corrector.

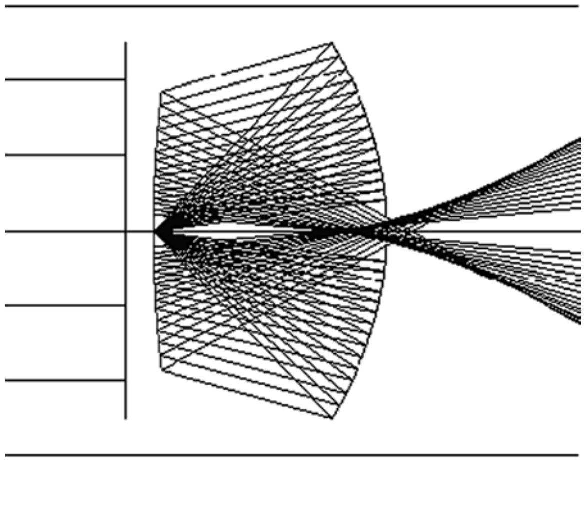


Fig. 1-23. Detailed ray trace of clamshell corrector.

infrastructure on the ground. At the present time, it appears that ground-based reception is the more appropriate choice. If one looks simply from an implementation cost standpoint, the cost estimates for an Earth-orbiting optical communications reception station are approximately the same as the costs required to implement an entire worldwide and spatially diversified ground network. This is comparing the ground net to just a single orbiting receiver. But, a single orbiting reception station would represent a single-point network failure risk that would take significant time to replace (months at a minimum if a standby spare spacecraft was available to years if a replacement development had to be restarted). This says that at least two orbital stations at a minimum would be required, if not more. This heavily weighs the balance toward the ground-based option. Furthermore, orbital receivers would have much shorter lifetimes, and they could not be maintained or upgraded like ground stations can be. Upgrades to new capabilities or wavelengths could not be phased in as easily as they could be on the ground, but would require engineering them in one of the next major block upgrades of the orbiting optical receiving terminal spacecraft series.

Continuous upgrades have been extremely important in the past history of the current DSN. For example, Fig. 1-24 shows the normalized (to Jupiter distance) increase in capability as a function of time that the DSN has achieved. Approximately 12 orders-of-magnitude of improvement in capability have occurred over the past 40 years. Most of this increase has been a result of transitions to higher communications frequencies (i.e., wavelength decreases). These changes have been implemented both on the user mission spacecraft and

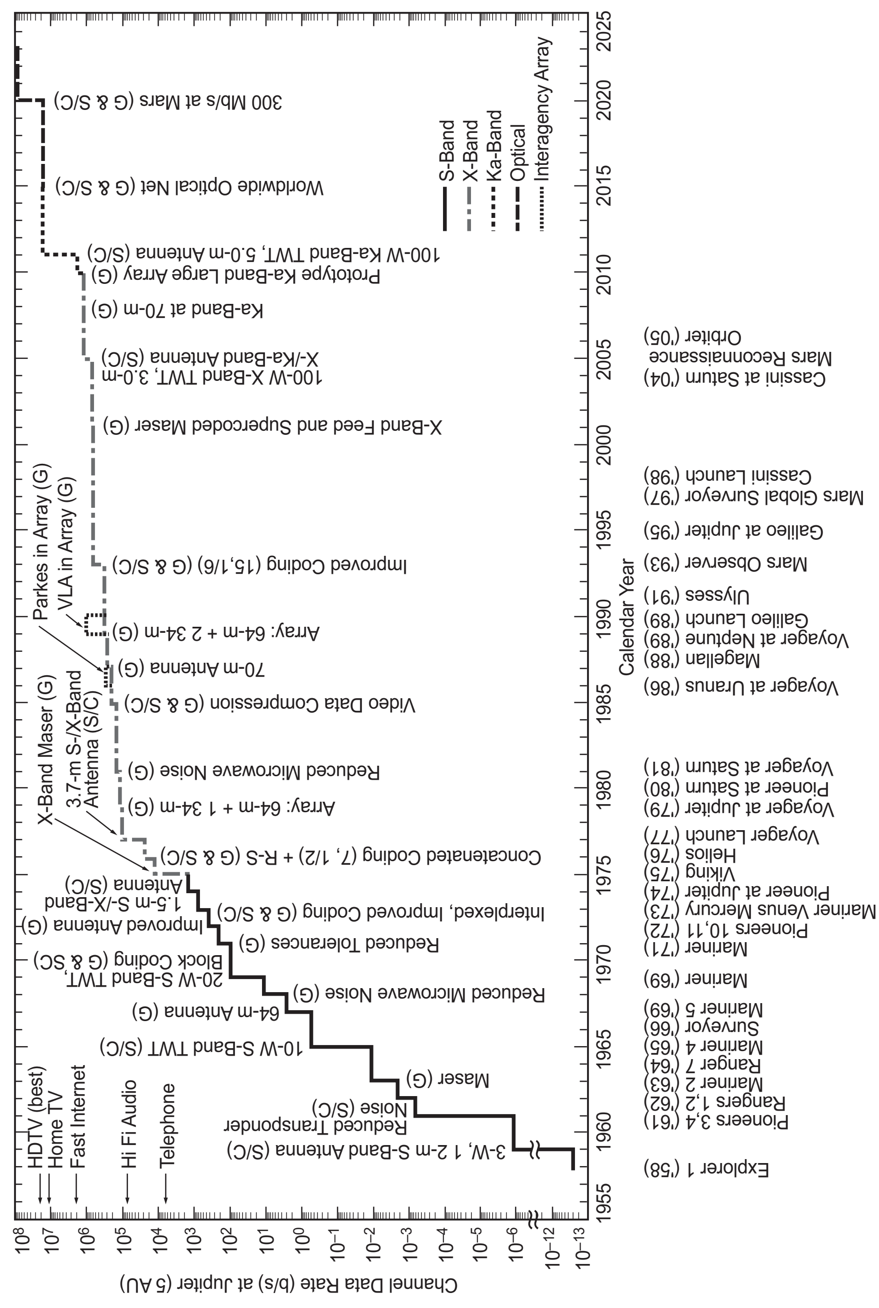


Fig. 1-24. Growth of normalized deep space communications capacity by improved ground (G) or spacecraft (S/C). (Note: major jumps in capability result from frequency changes.)

on the DSN. Having the reception systems accessible on the ground has been a key factor in enabling such a significant growth in capability. Had the DSN been in space, it would have severely restricted such growth to just the major orbital block upgrades, and would have resulted in increased technical risk for those block upgrades. Also, a 40-year longevity would have required a number of full orbital replacement cycles because of limited orbiting station lifetimes. It is clear that operational performance is a key factor in making future system architectural decisions, but the ultimate determining factor will be the overall life-cycle cost of the architectural options and will include all of these factors.

1.6 Atmospheric Transmission

In order to design a deep-space-to-ground optical communications link, it is necessary to understand the losses that will occur as the signal propagates through the atmosphere [100,101]. Both cloud blockages and atmospheric molecular absorption will impede the signal. Understanding the statistics on these losses is crucial so that the requirements for diversified reception (i.e., number of stations) and the resulting communications reliability can be determined. Molecular absorption is based on the percentages of different molecules in the atmosphere, and this effect can be reasonably well predicted using software tools developed over many years by the United States Air Force Research Laboratory (AFRL). As long as the wavelength used for communications does not lie on or very near a strong atmospheric absorption line, the clear-weather link attenuation is relatively constant. Clouds, on the other hand, occur much more randomly and can result in total extinction of the optical signal.

To assess cloud-cover statistics, JPL first obtained cloud-cover statistics taken from the Geostationary Operational Environmental Satellite (GOES) system. These statistics were in the form of cloud-cover contour maps provided by the University of Wisconsin [102], and clearly showed that clear skies are much more likely in the southwestern U.S. However, when comparing statistics, it was also evident that the sum of the clear-sky and cloudy-sky probabilities for a given spot was less than 1. The remaining probability mass is a result of partial cloudy conditions. Furthermore, it is important to know what defines clear or cloudy. Thin cirrus clouds may not show up on a satellite images as clouds, but they still result in some, albeit not always large, attenuation of the signal.

Realizing the need for more detailed statistics on atmospheric throughput, JPL created a program to make in situ measurements of the atmospheric throughput attenuation. To accomplish this, three atmospheric visibility monitoring (AVM) observatories were built and deployed in the southwestern U.S. [103–111]. One is located at Table Mountain, California, a JPL astronomical observatory site near the town of Wrightwood. The second AVM observatory is located at the DSN’s Goldstone Deep Space Communications Complex north of Barstow, California. The third is located on Mount Lemmon in Arizona.

Each AVM observatory contains a 25-cm telescope, a detector array, and several spectral filters on a filter wheel. The system is housed in a roll-off roof enclosure that is connected to a weather-sensing suite. The system operates autonomously, both day and night, to gather atmospheric throughput data by monitoring stars and measuring the stellar intensity on the ground in six spectral bands. By comparing the measured intensities of stars with the above-the-atmosphere values for those stars, the atmospheric throughput can be measured. The weather-sensing tower monitors for conditions at the site that would make telescope observation unsafe (i.e., high winds, rain/snow, excess humidity), and if such conditions are sensed, the enclosure roof and fold-down south-facing wall will close. Any time the enclosure is closed, or the system is not able to detect a star, the resident computer declares that the sky was totally cloudy. Otherwise, the observatory makes measurements of the stellar intensities and records them on the computer. Data are routinely transmitted back to JPL for processing and statistics generation. Figure 1-25 shows the AVM observatory at Table Mountain Facility (TMF) at Table Mountain, California. Figure 1-26 is a sample of a cumulative probability plot derived from the data. The horizontal axis is atmospheric attenuation (in decibels), and the vertical axis is cumulative probability. The two plots correspond to measurements made at two different wavelengths. For example, based on these

Fig. 1-25. Photograph of the AVM site at Table Mountain, California.

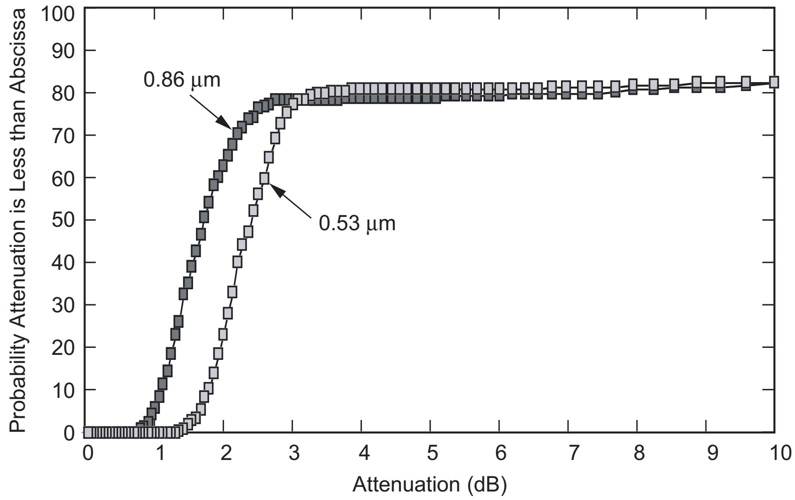


Fig. 1-26. Sample of cumulative atmospheric throughput at TMF (May-June 1996).

data, if an attenuation of 2 dB or less is required, optical reception at a wavelength of 0.53 µm will be possible about 20 percent of the time, but if a wavelength of 0.86 µm is used, the link is available about 60 percent of the time.

More recent studies of station availabilities have been developed through a contract with Northrup Grumman-TASC Corp. using updated satellite observation data [112].

1.7 Background Studies

Background light, whether from outside the atmosphere of the Earth or from within it, can become a severe limitation on system performance. Distant background light includes reflected sunlight from planetary surfaces, integrated starlight, and zodiacal light [113–115]. Of these, reflected planetary light is usually the only one of significance. Additionally, there can be scattered light interference, even for spaceborne receptions systems. Such light depends on many configuration parameters and on the orientation of the telescope relative to the Sun. For ground-based reception in the daylight, sunlight scattered by the atmosphere is the limiting factor for the receiver. Models have been in existence for many years for the level of this background source [116–119]. The actual levels of daytime background depend on many factors (including the telescope axis angle off the Sun, the amount of atmosphere through which the telescope is viewing, and the amount of particulate matter in the atmosphere).

The amount of background light that interferes with the signal detection or acquisition/tracking/pointing processes is also a function of the quality of the telescope. As noted above, photon-bucket (i.e., non-diffraction-limited) telescopes are of strong interest because they are much less expensive to build and maintain than precise diffraction-limited telescopes. But the larger blur circles associated with photon buckets mean that they will admit more dimensions of background light when the source of that light is distributed over space (particularly daytime skylight and background planetary light). Telescopes of a given aperture size will intercept the same amount of optical signal (which basically comes from a point source). That signal can be detected on those telescopes, provided the detectors at the focal planes are large enough to encompass the “blurred” focused spots. But the larger fields of view of larger detectors mean the detectors also capture more dimensions of the distributed background light. Thus, when considering trades for the precision of the telescope optics, it is often a trade between the background noise susceptibility of the system and the cost of the system.

1.8 Analysis Tools

Analysis of optical communications links is facilitated by the availability of a good set of link-performance prediction tools. The earliest JPL studies were based on the photon-counting channel where ideal Poisson-channel statistics dominated. Simple, first-order link calculations could be done by just considering the geometric aspects of the transmitted beam, the size and quality of the receiving aperture, and any prevailing sources of background noise [120,121]. More detailed calculations are facilitated by the use of specially designed computer programs. The first such program was called OPTI [122,123]. It was very basic, considered only ideal photon-counting detection, and ran on a 286-microprocessor personal computer. Later, a modified version of OPTI (called TOLER) was developed that had more detection options and included a very important feature to account for parameter tolerances [124]. In classical RF deep-space link designs, it is important to not only know the designed values of the link parameters, but to perform an analysis that can justify the amount of link margin required as well. Too little link margin means that if adverse tolerances or conditions mount up together, there might not be enough signal strength to adequately close the link. Too much link margin means that the system is over-designed and that unnecessarily large mass, power, or size (which all translate to increased cost) penalties were imposed on the system. Given the difficulty of deep-space communications and the tight budgets of the space program, managing these margins proactively is important.

As the optical communications program evolved, it became clear that there were many more modulations, codes, laser types, detectors, and background noise sources that needed to be included. Accordingly, a program called Free-Space Optical Communications Analysis Software (FOCAS) was developed [125]. Through several new-release updates, it has been the workhorse of the optical communications group for the past 15 years. Recently, the program has been ported to a web-based platform for a more general user community.

1.9 System-Level Studies

1.9.1 Venus Radar Mapping (VRM) Mission Study

In 1983 the first JPL mission application system study was done. It involved the Venus Orbiting Imaging Radar (VOIR) mission, later to be known as the Venus Radar Mapping (VRM) mission, and then finally as the Magellan mission. The purpose of the mission was to map the surface of Venus using an imaging radar. The spacecraft used a Voyager 3.7-m antenna, and the operational concept of the basic mission was to use that antenna as the transmit/receive antenna while radar mapping, and then to rotate the spacecraft to point the antenna toward Earth for relaying the captured radar data back to the DSN at X-band. To transmit data to Earth while mapping the planet would require a second antenna separately articulated on the spacecraft so it could point to Earth. This was clearly not practical. However, a much smaller but more capable self-contained and gimbaled communications terminal would allow simultaneous operation and would not require spacecraft attitude rolls for each communications pass. This seemed to be a natural application for an optical communications terminal. A study was conducted and concluded that a 98-kg flight terminal could return 4 Mbps from Venus to a 5-m ground receiver (the Mount Palomar, California, 5-m telescope was used in the study as a reference receiver). A drawing of the optical communications terminal is shown in Fig. 1-27, and a sketch of the spacecraft with the attached optical communications terminal is shown in Fig. 1-28. Although very desirable from a mission operational perspective, it was felt that the development of the flight terminal was too premature to meet the requirements for the mission launch schedule, so the decision was made not to pursue the development.

1.9.2 Synthetic Aperture Radar-C (SIR-C) Freeflyer

In 1994, the Space Shuttle flew the third flight of a synthetic aperture radar mission (SIR-C) in Earth orbit. Because of the success of the flight, there was a strong interest in a long-duration orbital mission called the SIR-C Freeflyer, but there was concern about how the data could be handled. On the SIR-C Shuttle flight, the data were recorded on magnetic tapes. To operate the SIR-C instrument on a long-duration flight mission, a high-data-rate link from the spacecraft to the ground would be required. Here again, optical communication was a natural solution. A link from Earth orbit to the ground, using the 10-cm-diameter OCD terminal on the spacecraft and a 1-m-diameter telescope on the ground, could easily transfer multiple gigabit/second (Gbps) data streams.

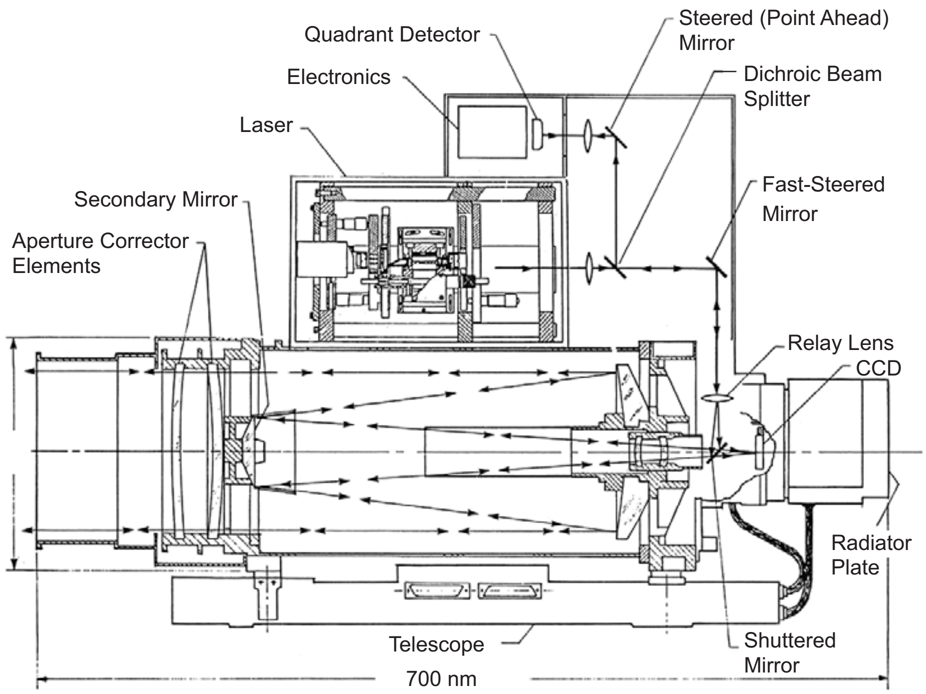


Fig. 1-27. Design of the VRM optical communication terminal.

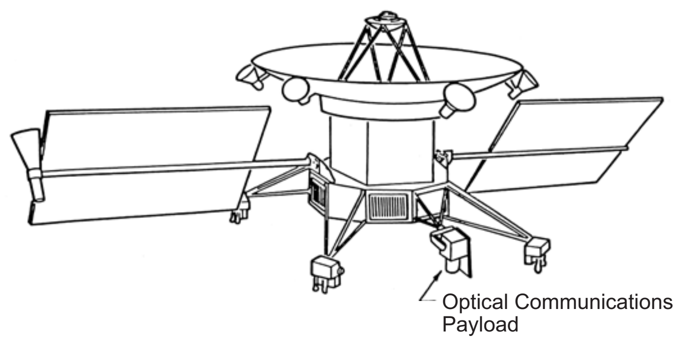


Fig. 1-28. VRM (Magellan) spacecraft with proposed optical terminal.

However, there was still concern that the optical communications technology was not adequately mature.

1.9.3 ER-2 to Ground Study

Given the experiences with the earlier OPTRANSPAC study targeted for Cassini and the earlier VRM flight terminal study, it was felt that some form of precursor flight demonstration of the optical communications capability would be needed. The targeted precursor was an aircraft-to-ground demonstration.

Initially, it was thought that the SR-71 aircraft (of which NASA had three) would be the best platform. However, after visiting the aircraft at NASA Dryden, and then viewing the ER-2 (NASA version of the U-2) aircraft at NASA Ames Research Center, it was concluded that the ER-2 could accommodate the payload much more easily. A detailed study of the use of the ER-2 aircraft with a flyable version of the OCD optical terminal was conducted [126]. The terminal would be mounted in the ER-2 "Q-bay" and would have to be operated without direct operator control.

The study also included provisions for an even earlier flight on the NASA DC-8 aircraft where operators could intervene if needed. Interest was strong in such a demonstration, but the interest dissipated when the ISSERT flight demonstration program awards (see Section 1.4.5) were announced, and it was felt that an air flight demonstration was no longer needed since a space flight demonstration program had already started.

1.9.4 Thousand Astronomical Unit (TAU) Mission and Interstellar Mission Studies

One of the attractions of optical communications is that the transmitted beam from the spacecraft diverges (i.e., dilutes) at a very slow rate as the beam propagates through space. This is of particular interest to really long-distance missions where the $1/R^2$ propagation losses can be enormous. An opportunity to see the real benefits of optical communications came up when JPL performed a study for a Thousand Astronomical Unit (TAU) mission (1 astronomical unit = mean Sun–Earth distance = 150 million km). Strong interest existed in such a mission because it was believed that the Oort cloud resided there and was essentially the factory for producing our Solar System's comets. Furthermore, such a mission was viewed as an excellent interstellar precursor mission. A study of the TAU mission was conducted, and it included an optical communications terminal for the return of data [127,128]. The design being considered would enable 20 kbps from a distance of 1000 AU. A drawing of the payload portion of the TAU spacecraft, which contains the optical communications terminal, is shown in Fig. 1-29.

The basic approach used in the TAU mission study was later applied and extended in a study for a full-interstellar mission to Alpha Centauri. Data rates up to 10 bps were projected from Alpha Centauri at 4.3 light years (271,000 AU or 40 trillion km) [129].

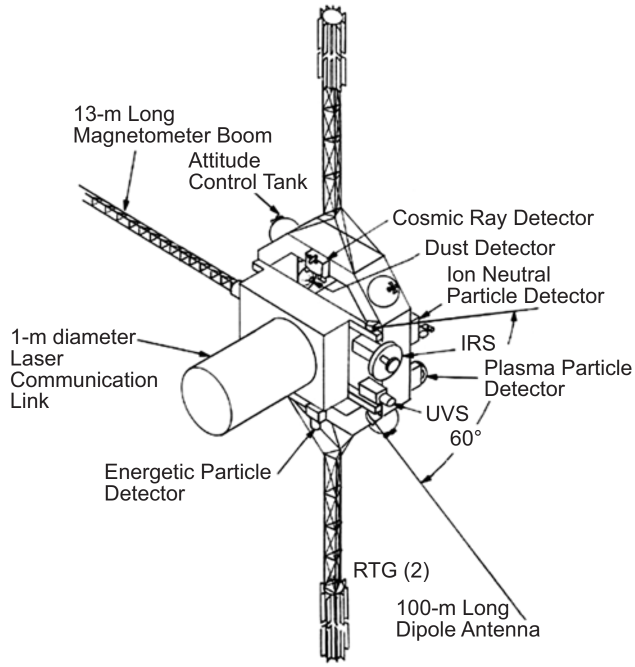


Fig. 1-29. TAU mission spacecraft design showing the optical terminal.

1.10 System-Level Demonstrations

1.10.1 Galileo Optical Experiment (GOPEX)

Although there were disappointments associated with the tight budgets and consequent cancellations of flight system developments, there were nevertheless some very successful and highly rewarding system-level demonstrations accomplished. One of these was performed in December of 1992 and involved the Galileo spacecraft. Recall that the similarities between an optical communications terminal and an imaging camera are quite high. In particular, a telescope with a focal-plane array constitutes a large part of the acquisition and tracking system for an optical communication terminal. Using this fact, a demonstration was conceived that used the imaging camera on the Galileo spacecraft to do an uplink optical communication demonstration.

The Galileo mission design included a trajectory that consisted of two returns to the vicinity of the Earth for trajectory-change gravity assists before traveling out toward Jupiter. Shortly after the second gravity assist in December 1992, a demonstration of uplink laser transmission to the spacecraft was conducted. The idea was to transmit pulsed laser signals from two optical ground telescopes. One was from the 60-cm telescope at TMF near

Wrightwood, California. The other was from the 1.5-m telescope at the Starfire Optical Range at Kirtland Air Force Base (AFB) in Albuquerque, New Mexico. The primary objective was to demonstrate that, based on spacecraft trajectory predicts and local stellar-mount calibrations of the ground telescopes, an uplink laser signal (simulating an uplink beacon) could be successfully transmitted to the spacecraft. The transmissions were done when the ground telescopes were in darkness. The reception of those laser signals was done by pointing the Galileo high-resolution imaging camera back to the Earth and using it as an optical communications receiver. During the demonstration, the Galileo camera shutter was opened, and the camera was scanned across the Earth in a direction parallel to the Earth's day–night boundary line. By doing this, individual laser pulses from a given ground telescope would fall on different pixels in a straight line across the camera's CCD focal-plane array. Transmissions from the two ground telescopes could be distinguished because they would appear as separated lines of dots at different lateral (i.e., Earth longitude) positions on the camera's focal-plane array. Additionally, the two uplink lasers had different pulse repetition frequencies (20 Hz and 30 Hz), so their spatial periods were different along their associated lines. Once the scan had traversed the angle necessary to cause the focused spots to move fully across the focal-plane array, the camera shutter was closed, and the integrated captured image (consisting of smeared Earthshine beyond the day–night terminator and the vertical lines of dots in the dark region of the array) was transmitted to the ground over the standard X-band RF communications link for processing at JPL's Mission Image Processing Laboratory. The resulting images were then analyzed to determine the uplink detection performance.

The demonstration, dubbed Galileo Optical Experiment (GOPEX) was conducted over a narrow window of eight nights, and one of those nights was a non-demonstration night because the spacecraft was scheduled to support other activities. Successful uplink detections occurred on all seven of the actual demonstration nights [130–138]. On certain nights both stations were available, and their signals were detected. On other nights, either one of the two stations was not operating due to poor weather or the signal transmitted by it was not detected due to excessive cloud attenuation. Still, the fact that successful detections were achieved on each night showed that open-loop predict-based uplink pointing was possible. It also showed the value of spatial diversity to circumvent weather outages.

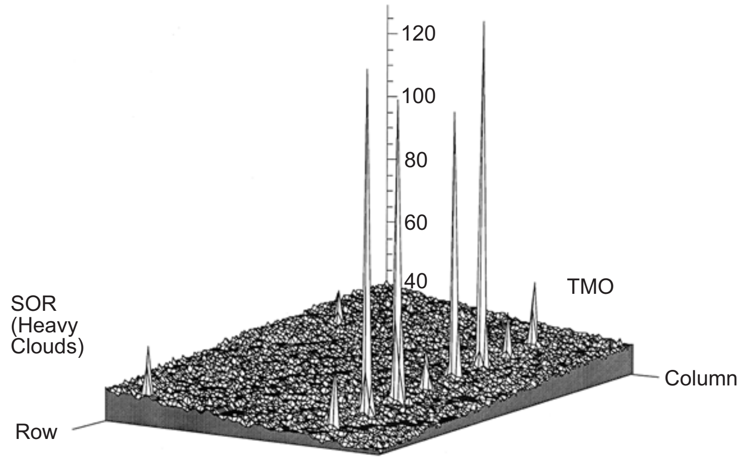
Figure 1-30 shows a sample image from one of the experiment days. Clearly evident in the image are smeared Earthshine and the two rows of laser-pulse detected dots. Note the different pulse detection periods associated with the individual stations. The first demonstration night occurred when the spacecraft was 600,000 km from the Earth. Successful detections on the last demonstration night were when the spacecraft was 6,000,000 km from the Earth. One of the key findings of the demonstration was that although the

Fig. 1-30. Earth image from Galileo spacecraft showing laser pulses (vertical rows of points).

pointing of the uplink beam was accurate enough to intercept the spacecraft, the scintillation on the uplink beam caused by atmospheric turbulence was quite severe. Figure 1-31 shows an intensity distribution of the detected pulses on one of the nights. This figure made it clear that some form of atmospheric turbulence mitigation would be needed to provide a stable intensity beacon signal at the spacecraft.

1.10.2 Compensated Earth–Moon–Earth Retro-Reflector Laser Link (CEMERLL)

The intensity variations of the uplink generated increased interest in adaptive optics (AO) for mitigating some of the effects of the atmospheric turbulence. The AFRL had just installed a new 3.5-m telescope at Starfire. Furthermore, they had an AO system already connected to their 1.5-m telescope at that facility. Through another cooperative arrangement with AFRL, a Compensated Earth–Moon–Earth Retro-reflector Laser Link (CEMERLL) demonstration was initiated. Laser signals were transmitted from the 1.5-m telescope toward the corner cube arrays that were left on the Moon by the Apollo astronauts. The 3.5-m telescope was used to collect the retro-reflected return signals. Initially, the uplink transmission did not use the AO system. Later the AO system was turned on with the aid of an artificial laser-beam-induced guide star. No discernible signal was detected when the AO system was not used. This was due to the fact that the atmospheric turbulence was breaking up the uplink signal and causing enough scintillation that the returned signal was too weak. When the AO system was engaged, significant return signals were detected at times [139].



SOR = Starfire Optical Range TMO = Table Mountain Observatory

Fig. 1-31. Typical pulse-height variations for laser signals received by Galileo spacecraft at a range of 2.2×10^6 km.

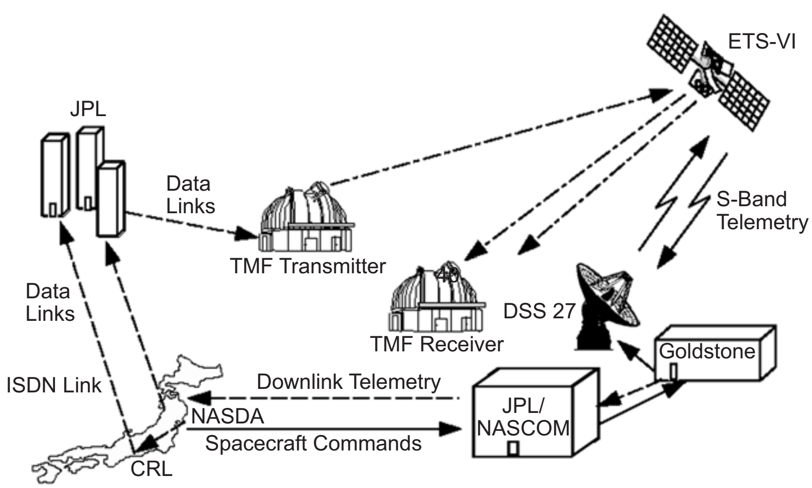
1.10.3 Ground/Orbiter Lasercomm Demonstration (GOLD)

In 1995 another space–ground optical communications opportunity came along. The Japanese had launched the ETS-VI spacecraft, an engineering test satellite, and on it was mounted a small laser communication terminal. The spacecraft was to be parked at GEO over Tokyo, and space–ground demonstrations were to be conducted between the satellite and a 1.5-m telescope at the Tokyo-based Communications Research Laboratory (CRL), a facility of the Japanese Ministry of Posts and Telecommunications. However, after getting into the elliptical transfer orbit required to reach GEO, the GEO-stabilizing rocket motor on the spacecraft failed. This left the spacecraft in the transfer orbit in which it reached to GEO-height altitudes over many countries. Through negotiations between NASA and the Japanese space agency (NASDA), an agreement was reached to do a cooperative space–ground demonstration using their spacecraft and ground telescopes at JPL's TMF.

Because of its orbit, the spacecraft passed over TMF at high altitude approximately every third night. In November of 1995, and after studying the details of the spacecraft and implementing the necessary equipment at Table Mountain (including a 14.5-W argon-ion laser), the Ground/Orbiter Lasercomm Demonstration (GOLD) operational phase commenced [140–145]. Every third night a 4–6 hour pass occurred, during which both uplink and downlink transmissions were made. The operational mode was for the ground station to send up a beacon (argon-ion laser) signal to the spacecraft. If the spacecraft saw the beacon, it would send down a laser signal using the beacon as a pointing reference. Once two-way beacon tracking was established, data modulation (at

1 Mbps) could be imposed on the uplink, on the downlink, or in a turn-around uplink–downlink mode. Sensors were located on the spacecraft to monitor many of the terminal operational parameters, including the uplink detected power levels. Similar instrumentation was installed at the ground. Uplink transmissions were accomplished using the TMF 0.6-m telescope that had been used for the GOPEX demonstration. Downlink signal reception was done at a neighboring 1.2-m telescope at TMF. Spacecraft terminal telemetry and performance data were transmitted via radio link to the DSN and then via NASA Communications (NASCOM) ground circuits to JPL before forwarding to NASDA and CRL. Processed data from those telemetry streams were then forwarded to TMF. The time delay in receipt of the processed spacecraft telemetry data at TMF was about 15 seconds. Having near-real-time data concerning the spacecraft terminal's performance was extremely helpful when conducting the demonstration activities. A diagram showing the end-to-end demonstration data flow is shown in Fig. 1-32.

The demonstration was conducted every third night from November 1995 through May of 1996, except for nights when the weather was bad at TMF. Actually, as the 6-month demonstration phase progressed, the times of the demonstration passes became later and later, until the end of the pass was well into the daytime. This provided experience with the additional effects of daytime sky-background interference. On almost all of the days, two-way lock-up of the links was achieved. And, on many of those days, long periods of solid signal strengths were observed. However, on other days the signals were



CRL = Communications Research Laboratory (Japan)
ISDN = Integrated Services Digital Network (NASA)
NASDA = National Space Development Agency (Japan)

Fig. 1-32. Data flow diagram for the GOLD demonstration.

observed to fade in and out. It was very difficult to diagnose all the variations, but it was generally believed that these variations were caused by attitude fluctuations of the spacecraft coupled with imprecise spacecraft adjustments for those fluctuations. Even at times when the signal strengths were steady, the bit error rates measured on the links were not always stable. The reasons for such variations were not isolated. Then again, there were also long periods when error-free communication was achieved. Figure 1-33 shows a sample of the demodulated data stream during one such occasion when the data reception quality was very good.

One of the key lessons learned from the GOPEX demonstration was that the uplink beacon often contains significant amounts of scintillation due to atmospheric turbulence (if not corrected). In the GOLD demonstration, there was no AO system installed. However, one of the objectives of the demonstration was to show that a multiple-beam uplink beacon signal could significantly reduce that scintillation. If a single beam is transmitted up through the atmosphere, the atmospheric turbulence will break that beam up into smaller beam segments that independently move around in angle due to local changes in the atmospheric refractive index. When these beam segments overlap at the spacecraft target, they can either combine in-phase or out-of-phase. In-phase events will cause a surge in power whereas out-of-phase events will cause severe signal fades. Such interference effects can give rise to very large fluctuations in the signal as seen at the spacecraft. However, if the beams are broken up into a bundle of beams before they enter the telescope, and if they are caused to be noncoherent relative to one another, then any overlapping of the beams at the spacecraft will result in an addition of the powers of the two beams. Furthermore, the probability of a really deep scintillation fade is very much reduced since it only occurs if all of the component beams simultaneously deflect away from the direction of the spacecraft (a much more unlikely event).

To implement this, the signal from the argon-ion laser was split using proportional beam splitters into two beams. Then one beam was delayed

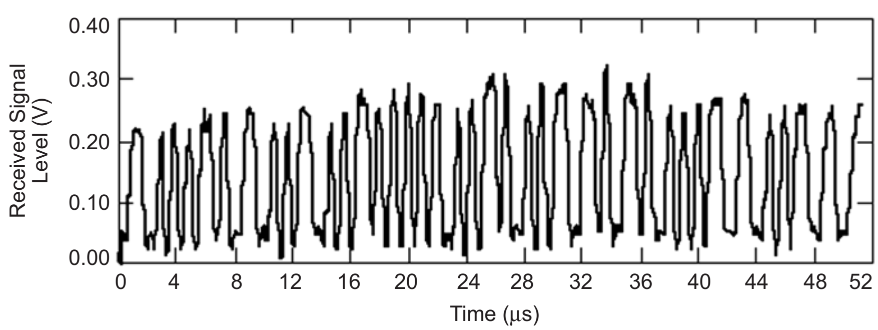


Fig. 1-33. Demodulated data patterns during the GOLD demonstration.

relative to the other so that it was outside the coherence length (and hence independent) of the other beam. Then each beam was sent up to different sub-aperture portions of the telescope primary mirror. Later, each of the two beams was in turn split (and delayed) so that a noncoherent four-beam uplink resulted. Figure 1-34 is a photograph of the uplink signal leaving the telescope when the four-beam transmission was used. Figure 1-35 shows uplink intensities as measured at the spacecraft for a single uplink beam of full power, a dual-beam uplink with half the power in each sub-beam, and finally a four-beam uplink with each beam containing 1/4 the power. As is clearly evident, the two-beam uplink has somewhat reduced the occurrence of really deep signal fades, whereas the four-beam uplink has very significantly reduced those uplink signal strength fades. Also shown in Fig. 1-35 are the histograms of the measured signal strengths at the spacecraft where these effects are even more evident.

1.10.4 Ground–Ground Demonstrations

Additional system-level demonstrations have taken place between ground stations. These have involved use of the 0.6-m telescope at Table Mountain and the Optical Communications Demonstrator engineering model terminal. Table Mountain is located at 2272 m (7400 ft) elevation in the eastern San Gabriel Mountains. The terrain drops off rapidly to the east, reaching down into the Cajon Pass, and then rises again at the western edge of the San Bernardino Mountains. A U.S. Forest Service tower is located at Strawberry Peak, a mountain peak on the eastern side of the pass. The 46-km line-of-sight path between Table Mountain and Strawberry Peak is an ideal place to conduct simulated space-to-ground optical links since most of the path is high above the

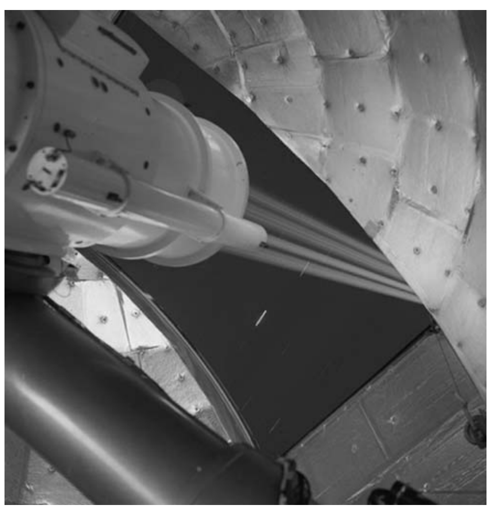


Fig. 1-34. Photograph of the four-beam uplink.

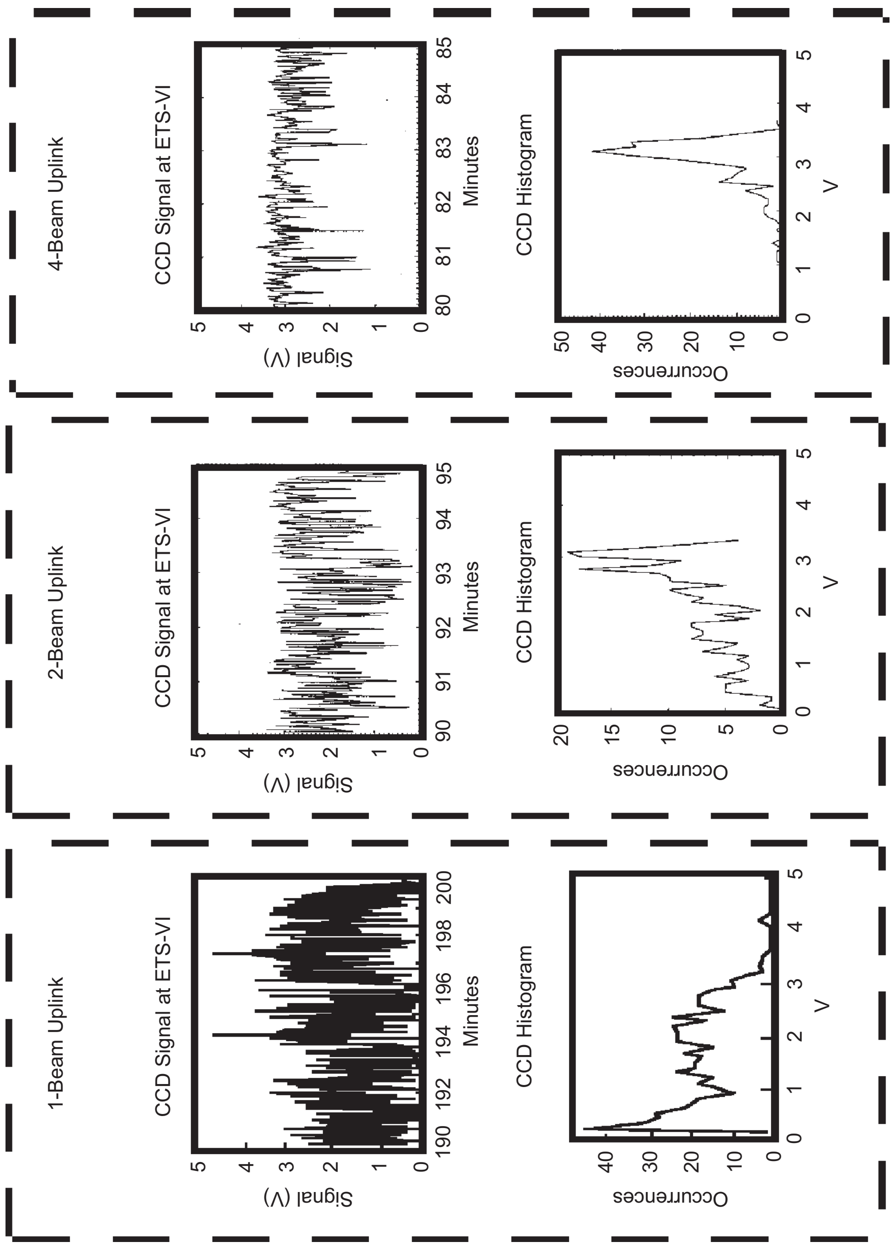


Fig. 1-35. Uplink signal intensities and intensity histograms for one-, two-, and four-beam uplinks.

ground and minimizes the horizontal path turbulence. The turbulence, although much less than that of most horizontal paths of the same length, is more characteristic of the worst case for typical space-to-ground links. A cross section of the path between these mountain peaks showing the height of the beam above the ground is provided in Fig. 1-36. A view of Table Mountain from the Strawberry Peak site is shown in Fig. 1-37.

Three separate experimental campaigns were conducted from June 1998 through September of 2000 [146–149]. The first two of these concentrated on

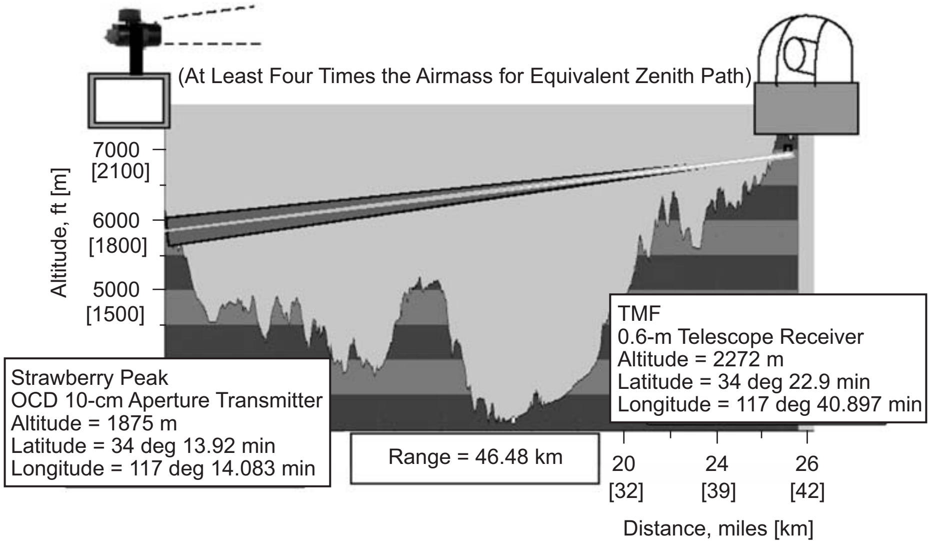


Fig. 1-36. Cross section of the path between TMF and Strawberry Peak.

Fig. 1-37. View of TMF from Strawberry Peak

characterizing the atmospheric turbulence and beam-wandering parameters for the link. The third focused on the performance of the OCD spatial acquisition and tracking system performance as well as the transmission of 400-Mbps data across the link. Measurements made during the campaign showed that uncompensated tracking jitter of ±1.1 μrad in the horizontal direction and ±2 μrad in the vertical direction could be achieved.

1.11 Other Telecommunication Functions

In standard RF deep-space communications systems, the signal is routinely used for more functions than just communications. Both navigation parameters and scientific measurements are integrated into the signal design for the link. For navigation, two-way ranging to the spacecraft, as well as the Doppler shift of the coherently tracked carrier signal, provide navigational tracking measurements. Two-way ranging can provide both distance to the spacecraft and (by differencing subsequent measurements) the velocity component of the trajectory. Doppler tracking, in conjunction with the Earth’s rotation about its axis, provides measurements of the angular location of the spacecraft in the sky. These angular measurements are often augmented by delta differential one-way ranging (DDOR) fixes for added angular measurement accuracy. DDOR uses pairs of intercontinentally spaced DSN tracking stations to make interferometric measurements of the arriving RF signals, first from the spacecraft, and then from an angularly close radio source (a distant quasar). By differencing these measurements, many of the error sources (e.g., station clock offsets, uncertainties of the station locations, and atmospheric delays) common to both measurements are cancelled out, leaving highly precise measures of the spacecraft location relative to the reference quasar positions. Angular measurement accuracies of spacecraft locations are often made to the 5-nrad accuracy level in this way.

Conventional RF communications system signals are also used to make “radio science” measurements. As the signal propagates back from deep space, its phase, amplitude, and/or polarization may be altered by things encountered in the propagation path. For example, as a spacecraft passes behind a planet, the return signal can be altered as it passes through the atmosphere of that planet. Another example is the phase jitter that can be imparted on the RF signal by charged-particle fluctuations from the solar wind as the signal passes close to the Sun.

1.11.1 Opto-Metric Navigation

It is desirable to be able to accomplish other functions with an optical communications signal as well, especially navigation measurements. An easy navigation measurement to make is that of two-way ranging. To accomplish this, a laser pulse can be sent on the uplink (i.e., on the beacon or on the command uplink) and detected on the spacecraft. The detected pulse is then used to trigger a pulse from the downlink laser. By measuring the time delay from the time the uplink pulse was generated to the time the downlink pulse is detected, and if the delays in the electronics of the spacecraft and ground systems are constant and calibrated, then the two-way path delay and hence distance can be calculated. This approach was included in the X2000 terminal development mentioned previously.

Angular measurements can also be made with optical signals [150–155]. Recall that for RF systems, multiple ground stations are used to interferometrically make angular measurements of the spacecraft location relative to the quasar reference catalog. With a ground-based optical telescope, the signal from the spacecraft can be focused onto a focal-plane detector array. The spot on the focal plane represents the location of the spacecraft, relative to the unknown axis of the telescope. However, if simultaneously the light from a stellar object is also collected, its energy will be concentrated onto a different location on the focal-plane detector. This spot represents the location of the star relative to the unknown telescope axis direction. Since both spots are on the same focal-plane detector at the same time, the vector difference between the two spot locations represents the angular offset of the spacecraft signal relative to the (catalog) star, irrespective of the actual axis of the telescope. Thus, for optical spacecraft-signal tracking, equivalent angular measurements to the RF interferometric systems can be made. In fact, they only require a single ground telescope. Furthermore, whereas the current RF DDOR technique requires independent measurements of the horizontal and vertical components of angles, an optical tracking telescope can make measurements in both directions at the same time. This technique has been used in optical astrometry, and it has yielded angular offsets between star pair measurements to accuracies of 5–10 nrad [156].

1.11.2 Light Science

In principle, scientific measurements should also be possible using optical communications signals, although more work needs to be done with the scientific community to fully develop these claims. Such measurements will not duplicate the specific measurements made today with RF systems, but will undoubtedly be complementary to them. One such example is the optical equivalent to RF occultation measurements. As a spacecraft moves behind a planet, the signal from its optical transmitter also passes through the planetary atmosphere. Measurements of the perturbations of that signal might reveal attributes of that atmosphere. Furthermore, the optical signal fluctuations will likely be much more sensitive to higher-altitude components of the atmosphere than are detectable with radio signals. As optical communications technology develops, and the use of the technology on future missions becomes more likely, it is believed that the scientific community will begin to recognize the scientific opportunities of this form of “Light Science.”

1.12 The Future

This past experience base provides a springboard for many of the planned activities of the future. These are both developmental activities as well as some exciting system demonstrations. Many of these will use the infrastructure already created, whereas others will result in the development and validation of new systems, tools, and techniques.

1.12.1 Optical Communications Telescope Laboratory (OCTL)

One of the key infrastructure elements recently created is the Optical Communications Telescope Laboratory (OCTL) [157–159]. Located at JPL’s TMF, OCTL will be the main ground support facility for a number of planned free-space optical communications demonstrations. Although there are a number of telescopes already at TMF, they are not well suited for use in the emerging set of planned demonstrations. Most of the current telescopes have inadequate space in their focal planes to accommodate the optical and electronic systems needed for planned future demonstrations, and none of the telescopes was designed for use during the daytime. The OCTL telescope is a 1-m-diameter diffraction-limited telescope that has a coudé focus and four coudé instrument rooms. Separate demonstrations can be set up in each of the coudé rooms. The telescope axis can be connected to one of these rooms by a coudé-room fold mirror (designated as M7). This will allow the telescope to be used while other demonstration setups are being installed in other rooms. Furthermore, the telescope is designed to operate within its diffraction-limited wavefront error tolerances down to solar offset angles of 30 percent. Although its wavefront errors will be degraded at smaller solar angles, the thermal control system will allow it to function at even smaller solar angles. Additionally, the telescope mount is capable of precision tracking of low-altitude satellites. This will allow it to support demonstrations that are relevant to near-Earth applications as well as deep-space applications. A photograph of the OCTL facility is shown in Fig. 1-38. A picture of the telescope assembly, with a clear view of the thermal control veins, is shown in Fig. 1-39.

1.12.2 Unmanned Arial Vehicle (UAV)–Ground Demonstration

One of the planned early demonstrations involves optical communications from an uncrewed airborne vehicle and the ground. Funded by the United States Missile Defense Agency, this activity will fly a modified version of the OCD terminal called the Optical Communications Terminal (OCT) on a Predator B unmanned aerial vehicle (UAV). The OCT will be outfitted with a

Fig. 1-38. The OCTL facility.

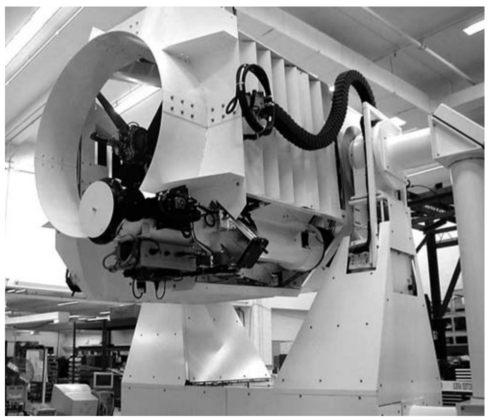


Fig. 1-39. The OCTL telescope.

1550-nm laser transmitter and will transmit at 2.5 Gbps from the UAV to the OCTL telescope. Reference [160] describes the UAV–Ground Demonstration program.

1.12.3 Adaptive Optics

One of the key technologies to be validated in the OCTL will be AO. As mentioned above, turbulence in the atmosphere can cause significant beam wander and intensity fluctuations on uplink beacon or command signals sent to distant spacecraft. Additionally, turbulence causes broadening of focused signal energy at the focal planes of ground-based receive telescopes. This broadening can drive the requirements for the detectors and result in increased susceptibility to background light interference. Under internal funding, JPL has been examining the use of AO techniques for optical communications.

AO techniques have been used in the past and are becoming commonplace on many astronomical observatories. Indeed, the JPL work is building directly on experiences gained by implementing AO on the Palomar and Keck telescopes [161–165]. These techniques have been used to sharpen images and enable astronomers to distinguish closely spaced celestial objects. Figure 1-40 is a diagram of the AO system on the Palomar 5-m telescope. It is located at the telescope's Cassagrain focus of the telescope, photographically shown in Fig. 1-41.

However, unlike astronomy observatories, optical communication ground stations must also operate in the daytime. This exacerbates the levels of turbulence that must be accommodated. Additionally, the overall objective is different for optical communications relative to astronomical observations. For astronomy, the objective is to increase the sharpness of images so that the finest

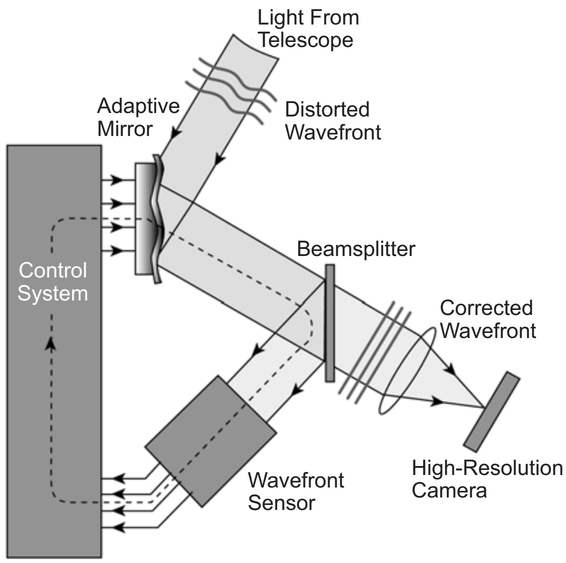


Fig. 1-40. Palomar AO layout.

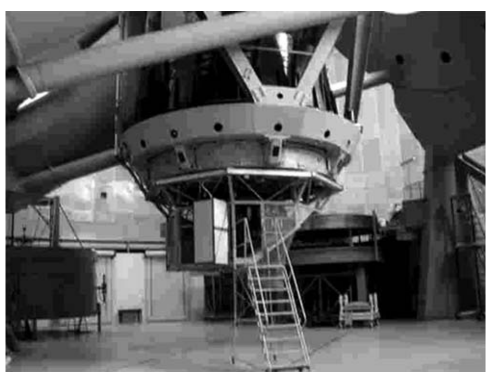


Fig. 1-41. Palomar Cassegrain focus.

details can be observed. If in the process there is a loss of signal energy, then that loss can be made up by just observing longer. For communications, the signal energy devoted to a given data bit is fixed, and must be conserved as much as possible. Thus, the optimization function for an optical communication AO system is to minimize the overall field of view (to minimize the amount of background light admitted) while maximizing the amount of desired signal energy captured (for the most robust signal detection) [166].

For uplink beacon and command links, the multi-beam transmission technique mentioned in the GOLD demonstration can be used to reduce some of the beam intensity fluctuations. Increased transmit power is easier to generate on the ground so that the beams can reach further into space. But, to reach even farther, or to reduce the uplink power requirements for a given distance, uplink AO will be beneficial. Such systems will likely rely on artificially generated laser guide-star calibrators to accomplish the uplink signal adaptation [167,168]. Both downlink signal-to-noise-ratio improvement and uplink beam-adaptive pre-distortion techniques can be validated using OCTL.

1.12.4 Optical Receiver and Dynamic Detector Array

Work is also continuing on the development of optical communication receivers to work at the focal plane of the reception telescopes. Such receivers must process electronic signals received from the downlink signal detectors and process them to extract the data modulation and the required temporal synchronization signals. Synchronization includes the recognition and dynamic tracking of slot synchronization (i.e., tracking the boundaries of the short intervals into which actual pulses could be placed, but which, due to the PPM modulation, are infrequently actually there) and PPM word synchronization (the places in the sequence of slots that define the beginning of a PPM symbol and from which the receiver must measure to extract the data bits associated with a given pulse). Additionally, higher levels of synchronization (such as frame or packet synchronization) may have to be accomplished in the receiver (or if not there, then certainly in the subsequent processing systems). Data detection assumes that synchronization has already been achieved and involves optimally processing the signals output from the detector to convert them to data bits that can be fed into the channel decoding system for error correction. Often the receiver is also required to provide soft (i.e., confidence) information to the decoder to improve its error-correction performance.

Another approach for efficient signal reception is an adaptive processing receiver that combines the photo-detection process and the front-end functions of the electronic signal processing [169–174]. This approach uses a focal-plane detector array whose outputs are combined through a weighting network. As the energy of the received signal is concentrated on the focal-plane array, local “hot spots” occur due to atmospheric turbulence. This receiver senses the regions on the focal plane where the signal is the strongest and weights those contributions more heavily than regions where the signal is weaker. Such a receiver can be used as an electronic form of AO, or it can be used in conjunction with an AO system to further compensate for residual turbulence-induced beam fluctuations. A photograph of such a detection and processing system is shown in Fig. 1-42.

1.12.5 Alternate Ground-Reception Systems

Work is also under way to assess alternate architectures for ground-based reception telescopes. In 2001 a JPL internally funded study was started to examine the use of a collection of smaller telescopes to act effectively as a single large telescope. Initial results indicate that, for ground-based reception systems, arrays of small telescopes, each with its own focal-plane detector system, can be an attractive alternative to large single-aperture-reception telescopes, especially if each telescope includes a focal-plane detector array for electronically tracking the atmospheric turbulence-induced “hot spots” [175–178]. Given these preliminary findings, an experimental program was initiated to validate the projections of such an array. A JMI Inc. 63-cm-diameter New Technology Telescope (NTT) was procured, and initial tests have begun. Although the results are promising, the ultimate conclusions will depend on a thorough understanding of the performance characteristics of both large single-aperture and arrayed smaller-aperture telescope architectures, as well as complete life-cycle-cost analyses of both approaches. A depiction of a reception array using 63-cm NTTs is shown in Fig. 1-43.

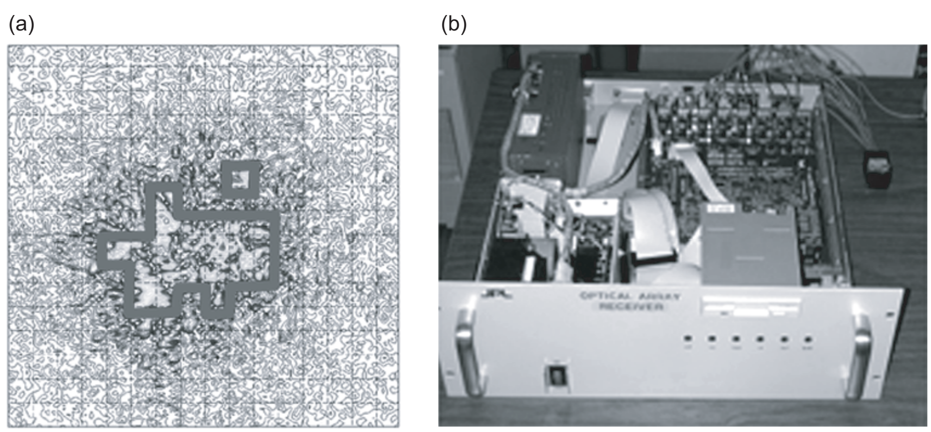


Fig. 1-42. 16×16 focal-plane array showing (a) higher-intensity pixels and (b) the 16×16 dynamic signal combiner.

Fig. 1-43. A large-aperture telescope made from an array of 63-cm telescopes.

1.13 Mars Laser Communication Demonstration

Over the past 25 years the key question has been, “When will optical communications be mature enough to use operationally?” The activities above have contributed significantly to the development and understanding of the technology, but there have been many major parallel development successes worldwide as well. In 1998, the European Space Agency launched an experimental optical communications terminal on the Satellite Probatoire d’Observation de la Terre (SPOT 4) French Earth observation satellite [179]. In 2001, they launched the companion terminal on the ARTEMIS satellite and demonstrated 50-Mbps links from the SPOT 4 in LEO to ARTEMIS in GEO [180]. The Japanese are also developing a terminal similar to the SPOT 4 terminal and hope to accomplish a similar demonstration to ARTEMIS [181]. The United States Defense Department has had a very successful flight demonstration involving the Geosynchronous Lightweight Technology Experiment (GEOLite) spacecraft. These and many other past studies, developments, and demonstrations have resulted in serious consideration of optical communications for the next generation of transformation communications systems. This intensified interest in the technology has led NASA to formulate a major initiative to demonstrate optical communication for deep-space applications.

To accomplish this, the Mars Laser Communications Demonstration (MLCD) project has been started. MLCD is a joint project of NASA Goddard Space Flight Center (GSFC), JPL, and Massachusetts Institute of Technology (MIT) Lincoln Laboratory. The basic objective is to demonstrate optical communications from Mars to the Earth at data rates from 1 through 10 Mbps, depending on specific conditions [52,182]. Indeed, under some conditions and if a 10-m-diameter ground-receiving telescope were available, data rates in the region of 100 Mbps would even be possible. The MLCD project will fly an optical communications terminal on the Mars Telesat Orbiter (MTO) that is planned for launch in 2009. An uplink laser signal will be transmitted to the spacecraft to act as a pointing reference beacon. The spacecraft terminal will track the beacon uplink and return a PPM-modulated downlink laser signal to the ground. Additionally, the flight terminal will have an inertial reference unit that will allow the spacecraft terminal to track a lower-power uplink beacon signal. This will simulate an even longer link and show that inertial reference systems can take up part of the tracking burden that relied on strong beacons in the past.

Several options are being assessed for the ground system demonstration support. Single large-aperture telescopes, both existing telescopes and possibly new ones, are being studied. Additionally, an array architecture is also being studied. The specific choices for this demonstration will depend on both technical performance and overall project cost constraints. But whatever the choices are, the demonstration promises to be a key milestone in the development of optical communication for deep space. Furthermore, the studies and developments associated with the MLCD project, when combined with thorough future mission load analyses and long-term infrastructure life-cycle-cost analyses, will provide valuable data for the subsequent definition and justification for the optical portions of the future Interplanetary Network [1].

1.14 Summary of Following Chapters

The remaining chapters of this book describe various aspects of deep-space optical communication systems in detail. They will provide both theoretical and practical considerations required in the realization of these future systems.

Chapter 2 begins with an overview of the end-to-end optical communications system, and then segues into some of the key design drivers for such links. One of these is the choice of the operating wavelength (equivalent to frequency selection in RF communication). Then, the Link Design Control Table (LDCT) is introduced, and a sample LDCT is given.

Chapter 3 presents the key attributes of the atmospheric channel. These include the effects of beam propagation, weather availability of links, the various background noise sources that degrade the optical channel, and how these factors affect choices for a potential optical deep-space network.

Chapter 4 summarizes efficient modulation and coding systems. The chapter begins with a discussion of the statistical models that describe the various methods of optical signal detection. Next, it presents descriptions of candidate modulation schemes. Given the detector statistics and the specific modulation schemes, the uncoded link performances of some of the more promising modulations with the candidate detectors are described. Given the modulation scheme and the kind of detector used, the resulting channel can be characterized in terms of its channel capacity. This is done for several of the more promising combinations of the two. Then, Chapter 4 describes codes that can be used over the resulting channels defined by the corresponding modulation and detection schemes. These codes are key to achieving data rates that approach channel capacity limits. Finally, it addresses and compares the performance of these coded systems.

Chapter 5 covers the key systems associated with an optical communications flight terminal. This begins with a section on the acquisition, tracking, and pointing (ATP) subsystem. Methods used to remove the errors associated with spacecraft platform jitter and to resolve uncertainties in the absolute direction needed for the transmitted beam are described. Next is a subsection describing laser transmitters. It covers both the methods of generating coherent laser energy and the systems used to modulate that energy. This leads to a subsection on the opto-mechanical subsystem that connects the laser and the ATP subsystems to the flight-unit telescope. It is important to understand both how these can be connected and the error sources that can impact the resulting system performance. Chapter 5 ends with a discussion of issues, challenges, and techniques associated with space qualification of the resulting flight terminal.

Chapter 6 describes the Earth reception terminal for a deep-space optical link. This chapter begins by considering the various types and possible locations of receiving telescopes. Next, the types of photo-detection schemes are described. This leads to a subsection on the remaining subsystems in the optical communications receiver that provide spatial acquisition and tracking, temporal synchronization, and demodulation/detection.

The final chapter provides concluding remarks and a look at the future prospects and expected applications of deep-space optical communications.

The challenges associated with deep-space communication are truly monumental, and the need for significantly increased deep-space communications capacity continues to grow. One of the promising technologies for overcoming these challenges and enabling substantial channel capacity growth is optical communication. This book provides a description of the systems required to achieve these gains and is the product of the collective knowledge of the past quarter century of effort in this field. In the future it is anticipated that optical communication will enable new kinds of deep-space missions to be flown that have heretofore been impractical to consider because of the difficulty in returning the required data. The resulting scientific discoveries will surely be awesome.

References

[1] W. J. Weber, R. J. Cesarone, D. S. Abraham, P. E. Doms, R. J. Doyle, C. D. Edwards, A. J. Hooke, J. R. Lesh, and R. B. Miller, "Transforming the Deep Space Network Into the Interplanetary network," Paper IAC-03-U.4.01 *54th International Astronautical Congress,* Bremen, Germany, September 29–October 3, 2003.

[2] J. R. Pierce, "Optical Channels: Practical Limits with Photon Counting," *IEEE Transactions on Communications*, vol. COMM-26, pp. 1819–1821, 1978.

[3] J. R. Lesh, J. Katz, H. H. Tan, and D. Zwillinger, "2.5-Bit/Detected Photon Demonstration Program: Description, Analysis, and Phase I Results," *The Telecommunications and Data Acquisition Progress Report 42-66, September and October 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 115–132, December 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[4] W. K. Marshall, "A PPM Modulator and Demodulator for the 2.5-Bit/Detected Photon Demonstration," *The Telecommunications and Data Acquisition Progress Report 42-68, January and February 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 50–54, April 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[5] J. Katz, "2.5 Bit/Detected Photon Demonstration Program: Phase II and III Experimental Results," *The Telecommunications and Data Acquisition Progress Report 42-70, May and June 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 95–104, August 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[6] H. H. Tan, "A Statistical Model of the Photomultiplier Gain Process With Applications to Optical Pulse Detection," *The Telecommunications and Data Acquisition Progress Report 42-68, January and February 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 55–67, April 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[7] J. R. Lesh, "Power Efficient Optical Communications for Space Applications," *Proceedings of 1982 International Telemetering Conference*, San Diego, California, pp. 109–113, September 28–30, 1982.

[8] J. R. Lesh, "Optical Communications Research Program to Demonstrate 2.5 Bits/Detected Photon," *IEEE Communications Magazine*, vol. 20, pp. 35–37, November 1982.

[9] R. J. Stokey and P. J. Lee, "Approximation to the Probability Density at Output of a Photomultiplier Tube," *The Telecommunications and Data Acquisition Progress Report 42-73*, *January–March 1983*, Jet Propulsion Laboratory, Pasadena, California, pp. 36–39, May 15, 1983. http://ipnpr.jpl.nasa.gov/progress_report/

[10] W. K. Marshall, "Detection and Symbol Synchronization for Multiple-Bit Per Photon Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-80, October–December 1984*, Jet Propulsion Laboratory, Pasadena, California, pp. 24–30, February 15, 1985. http://ipnpr.jpl.nasa.gov/progress_report/

[11] V. A. Vilnrotter, E. R. Rodemich, and H. H. Tan, "A Synchronization Technique for Optical PPM Signals," *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 24–31, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[12] R. J. McEliece and L. R. Welch, "Coding for Optical Channels With Photon-Counting," *The Deep Space Network Progress Report 42-52, May and June 1979*, Jet Propulsion Laboratory, Pasadena, California, pp. 61–66, August 15, 1979. http://ipnpr.jpl.nasa.gov/progress_report/

[13] L. D. Baumert, R. J. McEliece, and H. Rumsey, Jr., "Coding for Optical Channels," *The Deep Space Network Progress Report 42-49*, *November and December 1978*, Jet Propulsion Laboratory, Pasadena, California, pp. 70–77, February 15, 1979. http://ipnpr.jpl.nasa.gov/progress_report/

[14] R. J. McEliece, "Interleaved Block Codes for the Photon Channel," *The Telecommunications and Data Acquisition Progress Report 42-60*, *September and October 1980*, Jet Propulsion Laboratory, Pasadena, California, pp. 98–102, December 15, 1980. http://ipnpr.jpl.nasa.gov/progress_report/

[15] R. J. McEliece, "Practical Codes for the Photon Channel," *IEEE Transactions on Information Theory*, vol. IT-27, no. 4, pp. 393–398, July 1981.

[16] R. J. McEliece, "The R_0 Parameter for Optical Communication Using Photon Counting," *The Deep Space Network Progress Report 42-53*, *July and August 1979*, Jet Propulsion Laboratory, Pasadena, California, pp. 62–65, October 15, 1979. http://ipnpr.jpl.nasa.gov/progress_report/

[17] J. L. Massey, "Capacity, Cutoff Rate, and Coding for a Direct-Detection Optical Channel," *The Telecommunications and Data Acquisition Progress Report 42-60*, *September and October 1980*, Jet Propulsion Laboratory, Pasadena, California, pp. 68–76, December 15, 1980. http://ipnpr.jpl.nasa.gov/progress_report/

[18] J. R. Pierce, E. C. Posner, and E. R. Rodemich, "The Capacity of the Photon Channel," *IEEE Transactions on Information Theory,* vol. IT-27, no. 1, pp. 61–77, January 1981.

[19] H. H. Tan, "Capacity of a Multimode Direct Detection Optical Communication Channel," *The Telecommunications and Data Acquisition Progress Report 42-63*, *March and April 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 51–70, June 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[20] J. R. Lesh, "Capacity Limit of the Noiseless, Energy-Efficient Optical PPM Channel," *The Telecommunications and Data Acquisition Progress Report 42-67*, *November and December 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 54–58, February 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[21] J. R. Lesh, "Capacity Limit of the Noiseless, Energy-Efficient Optical PPM Channel," *IEEE Transactions on Communications*, vol. COMM-31, no. 4, pp. 546–548, April 1983.

[22] P. J. Lee, "Capacity and Cutoff Rate of (M + 1)-ary Decision Rules for Noisy M-ary Optical PPM Channel," *The Telecommunications and Data Acquisition Progress Report 42-72*, *October–December 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 43–50, February 15, 1983. http://ipnpr.jpl.nasa.gov/progress_report/

[23] J. Hamkins, "The Capacity of Avalanche Photodiode-Detected Pulse-Position Modulation," *The Telecommunications and Mission Operations Progress Report 42-138*, *April–June 1999*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–19, August 15, 1999. http://ipnpr.jpl.nasa.gov/progress_report/

[24] R. G. Lipes,, "Pulse-Position-Modulation Coding as Near-Optimum Utilization of Photon Counting Channel with Bandwidth and Power Constraints," *The Deep Space Network Progress Report 42-56*, *January and February 1980*, Jet Propulsion Laboratory, Pasadena, California, pp. 108–113, April 15, 1980. http://ipnpr.jpl.nasa.gov/progress_report/

[25] D. Zwillinger, "Maximizing Throughput Over an Average-Power-Limited and Band-Limited Optical Pulse Position Modulation Channel," *The Telecommunications and Data Acquisition Progress Report 42-62, January and February 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 81–86, April 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[26] S. J. Dolinar, Jr., "A Near-Optimum Receiver Structure for the Detection of M-ary Optical PPM Signals," *The Telecommunications and Data Acquisition Progress Report 42-72, October–December 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 30–42, February 15, 1983. http://ipnpr.jpl.nasa.gov/progress_report/

[27] P. J. Lee, "Analysis of a Coded, M-ary Orthogonal Input Optical Channel With Random-Gain Photomultiplier Detection," *The Telecommunications and Data Acquisition Progress Report 42-79, July–September 1984*, Jet Propulsion Laboratory, Pasadena, California, pp. 107–113, November 15, 1984. http://ipnpr.jpl.nasa.gov/progress_report/

[28] D. Divsalar and F. Naderi, "Performance of an Optical Relay Satellite Using Reed-Solomon Coding Over a Cascaded Optical PPM and BPSK Channel," *The Telecommunications and Data Acquisition Progress Report 42-70, May and June 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 117–131, August 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[29] D. Divsalar, R. M. Gagliardi, and J. H. Yuen, "PPM Demodulation for Reed-Solomon Decoding for the Optical Space Channel," *The Telecommunications and Data Acquisition Progress Report 42-70, May and June 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 47–59, August 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[30] R. J. McEliece and L. Swanson, "An Easy-to-Implement Coding Scheme for Multifrequency PPM," *The Telecommunications and Data Acquisition Progress Report 42-77, January–March 1984*, Jet Propulsion Laboratory, Pasadena, California, pp. 57–63, May 15, 1984. http://ipnpr.jpl.nasa.gov/progress_report/

[31] S. A. Butman, J. Katz, and J. R. Lesh, "Practical Limitations on Noiseless Optical Channel Capacity," *The Deep Space Network Progress Report 42-55, November and December 1979*, Jet Propulsion Laboratory, Pasadena, California, pp. 12–14, February 15, 1980. http://ipnpr.jpl.nasa.gov/progress_report/

[32] S. A. Butman, J. Katz, and J. R. Lesh, "Bandwidth Limitations of the Noiseless Optical Channel Capacity," *IEEE Transactions on Communications*, vol. COMM-30, pp. 1262–1264, May 1982.

[33] R. J. McEliece, E. R. Rodemich, and A. L. Rubin, "The Practical Limits of Photon Communication," *The Deep Space Network Progress Report 42-55, November and December 1979*, Jet Propulsion Laboratory, Pasadena, California, pp. 63–67, February 15, 1980. http://ipnpr.jpl.nasa.gov/progress_report/

[34] M. Ross, J. Abernathy, J. Wolf, P. Freedman, G. Matassov, and J. D. Barry, "Space Optical Communications with the Nd:YAG Laser," *Proceedings of the IEEE*, vol. 66, pp. 319–344, March 1, 1978.

[35] J. Katz, "High Power Semiconductor Lasers for Deep Space Communications," *The Telecommunications and Data Acquisition Progress Report 42-63*, *March and April 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 40–50, June 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[36] J. Katz, "Phase-Locking of Semiconductor Injection Lasers," *The Telecommunications and Data Acquisition Progress Report 42-66, September and October 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 101–114, December 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[37] J. Katz, "Power Efficiency of Semiconductor Injection Lasers," *The Telecommunications and Data Acquisition Progress Report 42-66, September and October 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 94–100, December 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[38] H. Hemmat, "Single Longitudinal Mode Operation of Semiconductor Laser Arrays With Etalon Control," *The Telecommunications and Data Acquisition Progress Report 42-86, April–June 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 66–69, August 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[39] J. Daher, "Preliminary Results Toward Injection Locking of an Incoherent Laser Array," *The Telecommunications and Data Acquisition Progress Report 42-84, October–December 1985*, Jet Propulsion Laboratory, Pasadena, California, pp. 26–34, February 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[40] J. Katz, "Power Combining of Semiconductor Lasers: A Review," *The Telecommunications and Data Acquisition Progress Report 42-70, May and June 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 87–94, August 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[41] J. Katz, "Phase Control and Beam Steering of Semiconductor Laser Arrays," *The Telecommunications and Data Acquisition Progress Report 42-68, January and February 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 42–49, April 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[42] J. Katz, "Electronic Beam Steering of Semiconductor Injection Lasers," *The Telecommunications and Data Acquisition Progress Report 42-68, January and February 1982*, Jet Propulsion Laboratory, Pasadena, California, pp. 25–41, April 15, 1982. http://ipnpr.jpl.nasa.gov/progress_report/

[43] D. L. Sipes, Jr., "Highly Efficient Nd:YAG Lasers for Free-Space Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-80, October–December 1984*, Jet Propulsion Laboratory, Pasadena, California, pp. 31–39, February 15, 1985.

[44] D. L. Sipes, "Highly Efficient Neodymium: Yttrium Aluminum Garnet Laser End-Pumped by a Semiconductor Laser Array," *Applied Physics Letters*, vol. 44, no. 2, pp. 74–76, July 15, 1985.

[45] D. L. Sipes, *Method and Apparatus for Efficient Operation of Optically Pumped Laser*, U.S. Patent 4,710,940, Washington, District of Columbia, December 1, 1987.

[46] W. K. Marshall, K. Cowles, and H. Hemmati, "Performance of Efficient Q-Switched Diode-Laser-Pumped Nd:YAG and Ho:YLF Lasers for Space Applications," *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 168–173, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[47] D. L. Robinson and M. D. Rayman, "Calculations of Laser Cavity Dumping for Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 174–179, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[48] H. Hemmati and J. R. Lesh, "Environmental Testing of a Diode-Laser-Pumped Nd:YAG Laser and a Set of Diode Laser Arrays," *Proceedings of SPIE Symposium on Space Sensing, Communications, and Networking*, paper 1059-22, January 1989.

[49] C. C. Chen, "Effect of Earth Albedo Variation on the Performance of a Spatial Acquisition Subsystem Aboard a Planetary Spacecraft," *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 202–211, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[50] G. G. Ortiz and S. Lee, "Acquisition, Tracking, and Pointing Using Earth Thermal Images for Deep Space Optical Communications," *2003 IEEE LEOS Annual Meeting Conference Proceedings, Tucson Arizona*, vol. 1, pp. 83–84, October 27, 2003, IEEE, Piscatawny, New Jersey, 2003.

[51] S. Lee, G. G. Ortiz, J. W. Alexander, A. Portillo, and C. Jeppesen, "Accelerometer-Assisted Tracking and Pointing for Deep Space Optical Communications," *IEEE Conference Proceedings*, Big Sky, Montana, vol. 3, pp. 31559–31564, March 10–17, 2001.

[52] B. Moision and J. Hamkins, "Deep-Space Optical Communications Downlink Budget: Modulation and Coding," *The Interplanetary Network Progress Report 42-154, April–June 2003*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–28, August 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[53] S. Lee, J. W. Alexander, and G. G. Ortiz, "Sub-Microradian Pointing for Deep Space Optical Telecommunications Network," presented at *19th AIAA International Communications Satellite Systems Conference*, Toulouse, France, 2001.

[54] G. G. Ortiz, A. Portillo, S. Lee, and Juan Ceniceros, "Functional Demonstration of Accelerometer-Assisted Beacon Tracking," in *Free-Space Laser Communication Technologies XIII, Proceedings of SPIE*, vol. 4272, pp. 112–117, 2001.

[55] J. Katz, "Detectors for Optical Communications: A Review," *The Telecommunications and Data Acquisition Progress Report 42-75, July–September 1983*, Jet Propulsion Laboratory, Pasadena, California, pp. 21–38, November 15, 1983. http://ipnpr.jpl.nasa.gov/progress_report/

[56] H. H. Tan, "Avalanche Photodiode Statistics in Triggered-Avalanche Detection Mode," *The Telecommunications and Data Acquisition Progress Report 42-79, July–September 1984*, Jet Propulsion Laboratory, Pasadena, California, pp. 69–80, November 15, 1984. http://ipnpr.jpl.nasa.gov/progress_report/

[57] D. L. Robinson and D. A. Hays, "Photon Detection With Cooled Avalanche Photodiodes: Theory and Preliminary Experimental Results," *The Telecommunications and Data Acquisition Progress Report 42-81, January–March 1985*, Jet Propulsion Laboratory, Pasadena, California, pp. 9–17, May 15, 1985. http://ipnpr.jpl.nasa.gov/progress_report/

[58] D. L Robinson and B. D. Metscher, "A Cooled Avalanche Photodiode With High Photon Detection Probability," *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 41–47, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[59] D. L. Robinson and R. D. Metscher, "Photon Detection with Cooled Avalanche Photodiodes," *Applied Physics Letters,* vol. 51, no. 19, pp. 1493–1494, November 9, 1987.

[60] C.-C. Chen, "Effect of Detector Dead Time on the Performance of Optical Direct-Detection Communication Links," *The Telecommunications and Data Acquisition Progress Report 42-93, January–March 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 146–154, May 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[61] A. Biswas and W. H. Farr, "Laboratory Characterization and Modeling of a Near-Infrared Enhanced Photomultiplier Tube," *The Interplanetary Network Progress Report 42-152, October–December 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–13, February 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[62] K. Shaik, "Spectral Filters for Laser Communications," *The Telecommunications and Data Acquisition Progress Report 42-106, April–June 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 93–101, August 15, 1991. http://ipnpr.jpl.nasa.gov/progress_report/

[63] E. L. Kerr, "Fraunhofer Filters to Reduce Solar Background for Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 48–55, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[64] B. Yin and T. M. Shay, "The Stark Anomalous Dispersion Optical Filter: The Theory," *The Telecommunications and Data Acquisition Progress Report 42-118, April–June 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 14–21, August 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/

[65] B. Yin, L. S. Alvarez, and T. M. Shay, "The Rb 780-Nanometer Faraday Anomalous Dispersion Optical Filter: Theory and Experiment," *The Telecommunications and Data Acquisition Progress Report 42-116, October–December 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 71–85, February 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/

[66] K. Kiasaleh and T.-Y. Yan, "T-PPM: A Novel Modulation Scheme for Optical Communication Systems Impaired by Pulse-Width Inaccuracies," *The Telecommunications and Mission Operations Progress Report 42-135, July–September 1998*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–16, November 15, 1998. http://ipnpr.jpl.nasa.gov/progress_report/

[67] M. Srinivasan, "Receiver Structure and Performance for Trellis-Coded Pulse-Position Modulation in Optical Communication Systems," *The Telecommunications and Mission Operations Progress Report 42-135, July–September 1998,* Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, November 15, 1998. http://ipnpr.jpl.nasa.gov/progress_report/

[68] J. Hamkins, "Performance of Binary Turbo-Coded 256-ary Pulse-Position Modulation," *The Telecommunications and Mission Operations Progress Report 42-138, April–June 1999*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–15, August 15, 1999. http://ipnpr.jpl.nasa.gov/progress_report/

[69] J. Hamkins, J. S. Dolinar, and D. Divsalar, "Optical Channel Capacity Sensitivity," *The Telecommunications and Mission Operations Progress Report 42-143, July–September 2000*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–16, November 15, 2000. http://ipnpr.jpl.nasa.gov/progress_report/

[70] B. Moision and J. Hamkins, "Constrained Coding for the Deep-Space Optical Channel," *The Interplanetary Network Progress Report 42-149, January–March 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1-29, May 15, 2002. http://ipnpr.jpl.nasa.gov/progress_report/

[71] S. G. Lambert, *Design and Analysis Study of a Spacecraft Optical Transceiver Package*, *Final Report – JPL Contract 957061*, McDonnell Douglas Corp., St. Louis, Missouri, August 19, 1985.

[72] J. Lesh, C.-C. Chen, and H. Ansari, *Lasercom System Architecture with Reduced Complexity*, U.S. Patent Number 5,517,016, Washington, District of Columbia, May 1996.

[73] M. Jeganathan, A. Portillo, C. S. Racho, S. Lee, D. M. Erickson, J. Depew, S. Monacos, and A. Biswas, "Lessons Learned from the Optical Communications Demonstrator (OCD)," *Free-Space Laser Communications Technologies XI, Proceedings of SPIE,* G. S. Mecherle, ed., vol. 3615, pp. 23–30, 1999.

[74] M. Jeganathan and S. Monacos, "Performance Analysis and Electronics Packaging of the Optical Communications Demonstrator," *Free-Space Laser Communications Technologies XI, Proceedings of SPIE,* G. S. Mecherle, ed., vol. 3226, p. 33, 1998.

[75] C. Racho and A. Portillo, "Tracking Performance Analysis and Simulation of the Digital Pointing System for the Optical Communication Demonstrator," *The Telecommunications and Mission Operations Progress Report 42-136, October–December 1998*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–13, February 15, 1999. http://ipnpr.jpl.nasa.gov/progress_report/

[76] C. Racho and A. Portillo, “Characterization and Design of Digital Pointing Subsystem for Optical Communication Demonstrator,” *Free-Space Laser Communication Technologies XI, Proceedings of the SPIE,* G. S. Mecherle, ed., vol. 3615, no. 15, pp. 250–261, January 1999.

[77] *X2000 Optical Communications Subsystem: Baseline Design Document for Europa-Orbiter Mission*, JPL D-30264 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 1998.

[78] J. R. Lesh and D. L. Robinson, “A Cost-Performance Model for Ground-Based Optical Communications Receiving Telescopes,” *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 56–64, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[79] D. L. Robinson and J. R. Lesh, “A Cost-Performance Model for Ground-Based Optical Communications Receiving Telescopes,” *Proceedings of SPIE OE Lase 87* (Optical Technologies for Space Communications, Los Angeles, California, January 15–16, 1987, paper 756-20), vol. 756, pp. 130–134, January 1987.

[80] V. A. Vilnrotter, *Optical Receivers, Using Rough Reflectors*, JPL Publication 85-25, Jet Propulsion Laboratory, Pasadena, California, May 1, 1985.

[81] E. L. Kerr, “Strawman Optical Reception Development Antenna (SORDA),” *The Telecommunications and Data Acquisition Progress Report 42-93, January–March 1988,* Jet Propulsion Laboratory, Pasadena, California, pp. 97–110, May 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[82] E. L. Kerr and C. W. DeVore, “Shutters and Slats for the Integral Sunshade of an Optical Reception Antenna,” *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 196–201, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[83] E. L. Kerr, “An Integral Sunshade for Optical Reception Antennas,” *The Telecommunications and Data Acquisition Progress Report 42-95, July–September 1988,* Jet Propulsion Laboratory, Pasadena, California, pp. 180–195, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[84] K. Shaik “Parameter Uncertainties for a 10-Meter Ground-Based Optical Reception Station,” *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp.118–127, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[85] K. Shaik, "A Two-Telescope Receiver Design for Deep Space Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-101, January–March 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 114–120, May 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[86] B. D. Clymer, "Active Optics for a Segmented Primary Mirror on a Deep-Space Optical Receiver Antenna (DSORA)," *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 128–134, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[87] B. D. Clymer, "Reflected Sunlight Reduction and Characterization for a Deep-Space Optical Receiver Antenna (DSORA)," *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 110–117, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[88] D. Wonica, "Research and Development Optical Deep Space Antenna Sizing Study," *The Telecommunications and Data Acquisition Progress Report 42-118, April–June 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 115–124, August 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/

[89] J. A. Hunter, *Orbiting Deep Space Relay Station Final Report*, JPL Publication 79-30, vols. 1, 2, 3, Jet Propulsion Laboratory, Pasadena, California, April 1, 1979.

[90] *DSRSS Concept Design and Technology Report*, JPL Contract 958734 Final Report, Stanford Telecommunications (TR93062), Reston, Virginia, July 7, 1993.

[91] *Deep Space Relay Satellite System Study Final Report*, JPL Contract No. 958733, TRW Federal Systems Division, Redondo Beach, California, September 20, 1993.

[92] K. Shaik and M. Wilhelm, "Ground Based Advanced Technology Study (GBATS): Optical Subnet Concepts for the DSN," JPL D-11000, Release 1 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 5, 1994.

[93] H. Hemmati, K. Wilson, M. K. Sue, L. J. Harcke, M. Wilhelm, C.-C. Chen, J. R. Lesh, Y. Feria, D. Rascoe, F. Lansing, and J. W. Layland, "Comparative Study of Optical and Radio-Frequency Communication Systems for a Deep-Space Mission," *The Telecommunications and Data Acquisition Progress Report 42-128, October–December 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–33, February 15, 1997. http://ipnpr.jpl.nasa.gov/progress_report/

[94] J. W. Layland, "Comparative Deep-Space Link Performance," *The Telecommunications and Mission Operations Progress Report 42–138, April–June 1999*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–12, August 15, 1999. http://ipnpr.jpl.nasa.gov/progress_report/

[95] K. E. Wilson, M. Wright, R. Cesarone, J. Ceniceros, and K. Shea, "Cost and Performance Comparison of an Earth-Orbiting Optical Communication Relay Transceiver and a Ground-Based Optical Receiver Subnet," *The Interplanetary Network Progress Report 42-153, January–March 2003*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–12, May 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[96] B. Levitt, K. Wilson, T. Roberts, R. Cesarone, and R. Hastrup, *Hybrid Optical DSN Architecture: Interleaved PPM Concept*, JPL D-30264 (internal document), Pasadena, California, November 1, 2004.

[97] J. V. Sandusky, D. J. Hoppe, and M. J. Britcliffe, "Deep-Space Optical Reception Antenna (DSORA): Aperture Versus Quality," *The Telecommunications and Mission Operations Progress Report 42-143, July–September 2000*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, November 15, 2000. http://ipnpr.jpl.nasa.gov/progress_report/

[98] M. J. Britcliffe and D. J. Hoppe, "Main-Reflector Manufacturing Technology for the Deep Space Optical Communications Ground Station," *The Telecommunications and Mission Operations Progress Report 42-145, January–March 2001*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–10, May 15, 2001. http://ipnpr.jpl.nasa.gov/progress_report/

[99] M. Britcliffe, D. Hoppe, W. Roberts, and N. Page, "A Ten-Meter Ground-Station Telescope for Deep-Space Optical Communications: A Preliminary Design," *The Interplanetary Network Progress Report 42-147, July–September 2001*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–17, November 15, 2001. http://ipnpr.jpl.nasa.gov/progress_report/

[100] K. S. Shaik, "Atmospheric Propagation Effects Relevant to Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-94, April–June 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 180–200, August 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[101] K. S. Shaik, "A Preliminary Weather Model for Optical Communications Through the Atmosphere," *The Telecommunications and Data Acquisition Progress Report 42-95*, *July–September*, Jet Propulsion Laboratory, Pasadena, California, pp. 212–218, November 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[102] D. P. Wyle, "Cloud Cover Statistics from GOES/VAS Satellite," *Proceedings of SPIE OE/Lase 88*, paper 874-34, Los Angeles California, January 1988.

[103] K. Cowles, "Site Selection Criteria for the Optical Atmospheric Visibility Monitoring Telescopes," *The Telecommunications and Data Acquisition Progress Report 42-97, January–March 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 235–239, May 15, 1989. http://ipnpr.jpl.nasa.gov/progress_report/

[104] K. Cowles, "A Visibility Characterization Program for Optical Communications Through The Atmosphere," *The Telecommunications and Data Acquisition Progress Report 42-97*, *January–March 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 221–225, May 15, 1989. http://ipnpr.jpl.nasa.gov/progress_report/

[105] D. Erickson and K. Cowles, "Options for Daytime Monitoring of Atmospheric Visibility in Optical Communications," *The Telecommunications and Data Acquisition Progress Report 42-97, January–March 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 226–234, May 15, 1989. http://ipnpr.jpl.nasa.gov/progress_report/

[106] K. A. Cowles, "Site Comparison for Optical Visibility Statistics in Southern Arizona," *The Telecommunications and Data Acquisition Progress Report 42-102*, *April–June 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 57–61, August 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[107] K. Cowles, "Site Comparison for Optical Visibility Statistics in Southern California," *The Telecommunications and Data Acquisition Progress Report 42-105*, *January–March 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 31–40, May 15, 1991. http://ipnpr.jpl.nasa.gov/progress_report/

[108] K. Cowles and D. Erickson, “Alignment of the Atmospheric Visibility Monitoring Telescope,” *The Telecommunications and Data Acquisition Progress Report 42-108, October–December 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 79–83, February 15, 1992. http://ipnpr.jpl.nasa.gov/progress_report/

[109] K. Cowles, “Hardware Design for the Autonomous Visibility Monitoring (AVM) Observatory,” *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 295–301, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[110] K. Cowles and B. M. Levine, “A Preliminary Optical Visibility Model,” *The Telecommunications and Data Acquisition Progress Report 42-119, July–September 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 201–209, November 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/

[111] B. Sanii, A. Datta, D. Tsiang, J. Wu, and A. Biswas, “Preliminary Results of an Upgraded Atmospheric Visibility Monitoring Station,” *The Telecommunications and Mission Operations Progress Report 42-142, April–June 2000*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–12, August 15, 2000. http://ipnpr.jpl.nasa.gov/progress_report/

[112] *NASA JPL CFLOS Study Final Review*, *JPL Contract 1248595 Final Briefing*, Northrop Grumman (TASC), Chantilly Virginia, September 26, 2003.

[113] J. Katz, “The Deep-Space Optical Channel: I. Noise Mechanisms,” *The Telecommunications and Data Acquisition Progress Report 42-64, May and June 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 180–186, August 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[114] J. Katz, “The Deep Space Optical Channel: II. Wave Propagation Effects,” *The Telecommunications and Data Acquisition Progress Report 42-65, July and August 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 53–58, October 15, 1981. http://ipnpr.jpl.nasa.gov/progress_report/

[115] J. Katz, “Planets as Background Noise Sources in Free Space Optical Communications,” *The Telecommunications and Data Acquisition Progress Report 42-85, January–March 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 13–24, May 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[116] W. L. Wolfe and G. J. Zissis, eds., *The Infrared Handbook*, Chapter 3, Environmental Research Institute of Michigan, Office of Naval Research, U.S. Department of the Navy, Washington, District of Columbia, 1978.

[117] E. E. Bell, L. Eisner, J. Young, and R. A. Oetjen, “Spectral Radiance of Sky and Terrain at Wavelengths between 1 and 20 microns: II—Sky Measurements,” *Journal of the Optical Society of America*, vol. 50, no. 12, pp. 1313–1320, December 1960.

[118] L. Eisner, E. E. Bell, J. Young, and R. A. Oetjen, “Spectral Radiance of Sky and Terrain at Wavelengths between 1 and 20 microns: III—Terrain Measurements,” *Journal of the Optical Society of America*, vol. 52, no. 2, pp. 201-209, February 1962.

[119] V. V. Vilnrotter, *Background Sources in Optical Communications*, JPL Publication 83-72, Jet Propulsion Laboratory, Pasadena, California, November 15, 1983.

[120] W. K. Marshall and B. D. Burk, “Received Optical Power Calculations for Optical Communications Link Performance Analysis,” *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 32–40, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[121] J. R. Lesh, W. K. Marshall, and J. Katz, “A Simple Method for Designing or Analyzing an Optical Communication Link,” *The Telecommunications and Data Acquisition Progress Report 42-85, January–March 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 25–31, May 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[122] W. K. Marshall and D. D. Burk, “Received Optical Power Calculations for Optical Communications Link Performance Analysis,” *The Telecommunications and Data Acquisition Progress Report 42–87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 32–40, November 15, 1986. http://ipnpr.jpl.nasa.gov/progress_report/

[123] *Optical Communications Link Analysis Computer Program*, *NASA New Technology Report*, NPO-17107, December 16, 1986.

[124] C.-C. Chen, “Design of an Optical PPM Communication Link in the Presence of Component Tolerances,” *The Telecommunications and Data Acquisition Progress Report 42-94, April–June 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 170–179, August 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[125] M. Jeganathan, G. S. Mecherle, and J. R. Lesh, “Development of the Free-space Optical Communications Analysis Software (FOCAS)” *Free-space Laser Communications Technologies X, Proceedings of SPIE*, G. S. Mecherle, ed., vol. 3266, pp. 90–98, 1998.

[126] J. R. Lesh, *Optical Communications Air-to-Ground Demonstration: Proposal Study*, JPL D-30265, (internal document), Jet Propulsion Laboratory, Pasadena, California, October 10, 1994.

[127] B. D. Metscher, "An Evaluation of the Communications System for the TAU Mission Study," *The Telecommunications and Data Acquisition Progress Report 42-89, January–March 1987*, Jet Propulsion Laboratory, Pasadena, California, pp. 108–117, April 1987. http://ipnpr.jpl.nasa.gov/progress_report/

[128] K. T. Nock, "TAU—A Mission to a Thousand Astronomical Units," *Proceedings of the 19th AIAA/DGLR/JSASS International Electric Propulsion Conference,* Colorado Springs, Colorado, Paper AIAA-87-1049, May 11–13, 1987.

[129] J. R. Lesh, C. J. Ruggier, and R. J. Cesarone, "Space Communications Technologies for Interstellar Missions" *Journal of the British Interplanetary Society*, vol. 49, pp. 7–14, 1996.

[130] K. E. Wilson, J. R. Lesh, T.-Y. Yan, J. Schwartz, M. D. Rayman, and S. Wee, "GOPEX: A Deep-Space Optical Communications Demonstration With the Galileo Spacecraft," *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 262–277, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[131] M. D. Rayman, "Selection and Observability Tests of GOPEX Reference Stars," *The Telecommunications and Data Acquisition Progress Report 42-103, July–September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 278–283, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[132] K. Kiesaleh and T.-Y. Yan, "A Statistical Model for Evaluating GOPEX Uplink Performance," *The Telecommunications and Data Acquisition Progress Report 42-111, July–September 1992*, Jet Propulsion Laboratory, Pasadena, California, pp. 325–332, November 15, 1992. http://ipnpr.jpl.nasa.gov/progress_report/

[133] R. Q. Fugate, "GOPEX at the Starfire Optical Range," *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 255–279, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[134] K. Shaik, D. Wonica, and M. Wilhelm, "Optical Subnet Concepts for the Deep Space Network," *The Telecommunications and Data Acquisition Progress Report 42-115, July–September 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 153–181, November 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[135] K. E. Wilson and J. R. Lesh, “An Overview of the Galileo Optical Experiment (GOPEX),” *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 192–204, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[136] J. Yu and M. Shao, “Galileo Optical Experiment (GOPEX) Optical Train: Design and Validation at the Table Mountain Facility,” *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 236–247, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[137] G. Okamoto and K. Masters, “GOPEX Laser Transmission and Monitoring Systems,” *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 248–254, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[138] A. Biswas, “Calibration of the Receiver Channel for the GOPEX Precursor Experiments,” *The Telecommunications and Data Acquisition Progress Report 42-114, April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 205–212, August 15, 1993. http://ipnpr.jpl.nasa.gov/progress_report/

[139] K. E. Wilson, P. R. Leatherman, R. Cleis, J. Spinhirne, and R. Q. Fugate, “Results of the Compensated Earth–Moon–Earth Retroreflector Laser Link (CEMERLL) Experiment,” *The Telecommunications and Data Acquisition Progress Report 42-131, July–September 1997*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–13, November 15, 1997. http://ipnpr.jpl.nasa.gov/progress_report/

[140] S. D. Gillam, J. W. Young, and D. R. Sidwell, “JPL Table Mountain Facility Support of the Ground/Orbiter Lasercomm Demonstration,” *The Telecommunications and Data Acquisition Progress Report 42-125, January–March 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, May 15, 1996. http://ipnpr.jpl.nasa.gov/progress_report/

[141] M. Jeganathan, K. E. Wilson, and J. R. Lesh, “Preliminary Analysis of Fluctuations in the Received Uplink-Beacon-Power Data Obtained From the GOLD Experiments,” *The Telecommunications and Data Acquisition Progress Report 42-124, October–December 1995*, Jet Propulsion Laboratory, Pasadena, California, pp. 20–32, February 15, 1996. http://ipnpr.jpl.nasa.gov/progress_report/

[142] K. E. Wilson, "An Overview of the GOLD Experiment Between the ETS-VI Satellite and the Table Mountain Facility," *The Telecommunications and Data Acquisition Progress Report 42-124, October–December 1995*, Jet Propulsion Laboratory, Pasadena, California, pp. 8–19, February 15, 1996. http://ipnpr.jpl.nasa.gov/progress_report/

[143] K. Wilson, M. Jeganathan, J. R. Lesh, J. James, and G. Xu, "Results From Phase-1 and Phase-2 GOLD Experiments," *The Telecommunications and Data Acquisition Progress Report 42-128, October–December 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, February 15, 1997. http://ipnpr.jpl.nasa.gov/progress_report/

[144] C. Pasqualino, "Characterization of the Avalanche Photo Diode Detector Used for Optical Communications Experiments With the Japanese ETS-VI," *The Telecommunications and Data Acquisition Progress Report 42-128, October–December 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–8, February 15, 1997. http://ipnpr.jpl.nasa.gov/progress_report/

[145] M. Toyoshima, K. Araki, Y. Arimoto, M. Toyoda, M. Jeganathan, K. Wilson, and J. R. Lesh, "Reduction of ETS-VI Laser Communication Equipment Optical-Downlink Telemetry Collected During GOLD," *The Telecommunications and Data Acquisition Progress Report 42-128, October–December 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–9, February 15, 1997. http://ipnpr.jpl.nasa.gov/progress_report/

[146] A. Biswas and S. Lee, "Ground-to-Ground Optical Communications Demonstration," *The Telecommunications and Mission Operations Progress Report 42-141, January–March 2000*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–31, May 15, 2000. http://ipnpr.jpl.nasa.gov/progress_report/

[147] A. Biswas and M. W. Wright, "Mountain-Top-to-Mountain-Top Optical Link Demonstration: Part I," *The Interplanetary Network Progress Report 42-149, January–March 2002,* Jet Propulsion Laboratory, Pasadena, California, pp. 1–27, May 15, 2002. http://ipnpr.jpl.nasa.gov/progress_report/

[148] A. Biswas, M. W. Wright, B. Samii, and W. A Page, "45-km Horizontal Path Optical Link Demonstration," *Proceedings of SPIE, Free-Space Laser Communications Technologies XIII*, G. S. Mecherle, ed., vol. 4272, pp. 60–71, 2001.

[149] A. Biswas and M. W. Wright, "Mountain-Top-to-Mountain-Top Optical Link Demonstration: Part II," *The Interplanetary Network Progress Report 42-151, July–September 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–16, November 15, 2002. http://ipnpr.jpl.nasa.gov/progress_report/

[150] B. L. Schumaker, "Apparent Brightness of Stars and Lasers," *The Telecommunications and Data Acquisition Progress Report 42-93, January–March 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 111–130, May 15, 1988. http://ipnpr.jpl.nasa.gov/progress_report/

[151] W. M. Folkner and M. H. Finger, "Photon Statistical Limitations for Daytime Optical Tracking," *The Telecommunications and Data Acquisition Progress Report 42-99, July-September 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 90–97, November 15, 1989. http://ipnpr.jpl.nasa.gov/progress_report/

[152] G. W. Null and P. W. Chodas, "Optical Self-Crossing Measurements for Ida Ephemeris Improvement," *The Telecommunications and Data Acquisition Progress Report 42-103, July-September 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 87–96, November 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[153] W. M. Folkner and M. H. Finger, "Preliminary Error Budget for an Optical Ranging System: Range, Range Rate, and Differenced Range Observables," *The Telecommunications and Data Acquisition Progress Report 42-101, January–March 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 121–135, May 15, 1990. http://ipnpr.jpl.nasa.gov/progress_report/

[154] G. W. Null, W. M. Owen, Jr., and S. P. Synnott, "Deep-Space Navigation Applications of Improved Ground-Based Optical Astrometry," *The Telecommunications and Data Acquisition Progress Report 42-110, April–June 1992*, Jet Propulsion Laboratory, Pasadena, California, pp. 118–127, August 15, 1992. http://ipnpr.jpl.nasa.gov/progress_report/

[155] G. W. Null, W. M. Owen, Jr., and S. P. Synnott, "Systems Analysis for Ground-Based Optical Navigation," *The Telecommunications and Data Acquisition Progress Report 42-111, July–September 1992*, Jet Propulsion Laboratory, Pasadena, California, pp. 23–40, November 15, 1992. http://ipnpr.jpl.nasa.gov/progress_report/

[156] G. D. Gatewood, "The Multichannel Astrometric Photometer and Atmospheric Limitations in the Measurement of Relative Precisions," *Astronomical Journal*, vol. 94, no. 1, pp. 213–224, 1987.

[157] K. E. Wilson, M. Britcliffe, and N. Golshan, “Progress in Design and Construction of the Optical Communications Laser Laboratory,” *The Telecommunications and Mission Operations Progress Report 42-138, April–June 1999,* Jet Propulsion Laboratory, Pasadena, California, pp. 1–6, August 15, 1999. http://ipnpr.jpl.nasa.gov/progress_report/

[158] K. E. Wilson, W. T. Roberts, V. Garkanian, F. Battle, R. Leblanc, H. Hemmati, and P. Robles, “Plan for Safe Laser Beam Propagation from the Optical Communications Telescope Laboratory,” *The Interplanetary Network Progress Report 42-152, October–December 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–17, February 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[159] K. E. Wilson, N. Page, J. Wu, and M. Srinivasan, “The JPL Optical Communications Telescope Laboratory Test Bed for the Future Optical Deep Space Network,” *The Interplanetary Network Progress Report 42-153, January–March 2003*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–8, May 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[160] G. G. Ortiz, S. Lee, S. P. Monacos, M. W. Wright, and A. Biswas, “Design and development of a robust ATP subsystem for the Altair UAV-to-Ground Lasercom 2.5 Gbps Demonstration,” *Free-Space Laser Communications Technologies XV*, *Proceedings of SPIE*, G. S. Mecherle, ed., vol. 4975, pp. 103–114, January 28, 2003.

[161] M. Troy, R. Dekany, G. Brack, B. Oppenheimer, E. Bloemhof, T. Trinh, F. Dekens, F. Shi, T. Hayward, and B. Brandl, “Palomar Adaptive Optics Project: Status and Performance,” *Proceedings of SPIE*, vol. 4007, pp. 31–40, 2000.

[162] T. L. Hayward, B. Brandl, B. Pirger, C. Blackenm, G. E. Gull, J. Schoenwald, and J. R. Houck, “PHARO-A Near-Infrared Camera for the Palomar Adaptive Optics System,” *Publications of the Astronomical Society of the Pacific (PASP)*, vol. 113, no. 779, pp. 105–118, January 2001.

[163] T. Truong, G. Brack, M. Troy, T. Trinh, F. Shi, and R. Dekany, “Real-Time Wavefront Processors for the Next Generation of Adaptive Optics Systems: A Design and Analysis,” *Proceedings of SPIE*, vol. 4839, pp. 911–922, 2003.

[164] M. A. van Dam and B. A. Macintosh, “Characterization of adaptive optics at Keck Observatory,” *Astronomical Adaptive Optics Systems and Applications*, R. K. Tyson and M. Lloyd-Hart, eds., *Proceedings of SPIE*, vol. 5169, pp. 1–10, 2003.

[165] R. Dekany, B. Bauman, D. Gavel, M. Troy, B. Macintosh, and M. Britton, "Initial Concepts for CELT Adaptive Optics," *Proceedings of SPIE*, vol. 4839, pp. 1165–1174, 2003.

[166] K. Wilson, M. Troy, M. Srinivasan, B. Platt, V. Vilnrotter, M. Wright, V. Garkanian, and H. Hemmati, "Daytime Adaptive Optics For Deep Space Optical Communications," *Space Activities and Cooperation Contributing to All Pacific Basin Countries: Tenth International Space Conference of Pacific Basin Countries, ISCOPS*, Tokyo, Japan, December 10–12, P. M. Bainum, L. Furong, and T. Nakajima, eds., American Astronomical Society, pp. 481–492, 2003.

[167] W. Happer, G. J. MacDonald, C. E. Max, and F. J. Dyson, "Atmospheric Turbulence Compensation by Resonant Optical Backscattering from the Sodium Layer in the Upper Atmosphere," *Journal of the Optical Society of America*, vol. A 11, p. 263, 1994.

[168] R. Q. Fugate, B. L. Ellerbroek, C. H. Higgings, M. P. Jelonek, W. J. Lange, A. C. Slavin, W. J. Wild, D. M. Winker, J. M. Wynia, J. M. Spinhirne, B. R. Boeke, R. E. Ruane, J. F. Moroney, M. D. Oliker, D. W. Swindle, and R. A. Cleis, "Two Generations of Laser-Guide-Star Adaptive-Optics Experiments at the Starfire Optical Range," *JOSA A*, vol. 11, no. 1, pp. 310–324, 1994.

[169] V. Vilnrotter and M. Srinivasan, "Adaptive Detector Arrays for Optical Communications Receivers," *IEEE Transactions on Communications*, vol. 50, no. 7, pp. 1091–1097, July 2002.

[170] V. Vilnrotter and M. Srinivasan, "Optical Communications through Atmospheric Turbulence Using Photodetector Arrays," *Free-Space Laser Communication Technologies XIII, Proceedings of SPIE*, vol. 4272, pp. 282– 292, San Jose, January 2001.

[171] V. Vilnrotter and M. Srinivasan, "Adaptive Detector Arrays for Optical Communications Receivers," *The Telecommunications and Mission Operations Progress Report 42–141, January–March 2000*, Jet Propulsion Laboratory, Pasadena, California, May 15, 2000. http://ipnpr.jpl.nasa.gov/progress_report/

[172] M. Srinivasan and V. Vilnrotter, "Avalanche Photodiode Arrays for Optical Communications Receivers," the *Telecommunications and Mission Operations Progress Report 42–144, October–December 2000*, Jet Propulsion Laboratory, Pasadena, California, February 15, 2001. http://ipnpr.jpl.nasa.gov/progress_report/

[173] V. Vilnrotter and M. Srinivasan, "Adaptive Optical Array Receiver: Communicating through Atmospheric Turbulence," *IND Science and Technology News*, JPL 410-62, Jet Propulsion Laboratory, Pasadena, California, issue 14, pp. 14–18, September 2001. http://tmot.jpl.nasa.gov/Program_Overview_Information/IND_Program_News/

[174] M. Munoz and V. Vilnrotter, "Coherent Optical Receiver for PPM Signals Received through Atmospheric Turbulence," *Free-Space Laser Communications Technologies XVI, Proceedings of SPIE*, vol. 5338, pp. 151–163, San Jose, January 2004.

[175] V. Vilnrotter, C.-W. Lau, M. Srinivasan, R. Mukai, and K. Andrews, "An Optical Array Receiver for Deep-Space Communication through Atmospheric Turbulence," *The Interplanetary Network Progress Report 42-154, April–June, 2003*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–21, August 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[176] V. Vilnrotter, C.-W. Lau, M. Srinivasan, R. Mukai, and K. Andrews, "Optical Array Receivers for Deep Space Communication," *Space Activities and Cooperation Contributing to All Pacific Basin Countries: Tenth International Space Conference of Pacific-Basin Societies;* P. M. Bainum, L. Furong, and Takashi Nakajima, eds., ISCOPS Conference, Tokyo, Japan, December 10–12, 2003, vol. 117, pp. 493–510, 2004.

[177] V. Vilnrotter, C.-W. Lau, and M. Srinivasan, "Optical Array Receiver for Deep-Space Communications," *Free Space Laser Communication Technologies XVI, Proceedings of SPIE*, G. S. Mecherle, C. Y. Young, and J. S. Stryjewski, eds., pp. 163–174, June 2004.

[178] V. Vilnrotter, K. Andrews, and C.-W. Lau, "Conceptual Design of an Optical Array Receiver with Preliminary Experimental Results," *The Interplanetary Network Progress Report 42–156*, Jet Propulsion Laboratory, Pasadena, California, February 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/

[179] T. Tolker-Nielsen, B. Demelenne, and E. Desplats, "In-orbit Test Results of the First SILEX Terminal," *Free-Space Laser Communication Technologies XI*, *Proceedings of SPIE*, vol. 3615, pp. 31–42, , San Jose, California, January 1999.

[180] T. Tolker-Nielsen and G. Oppenhauser, "In-Orbit Test Result of an Operational Intersatellite Link between ARTEMIS and SPOT 4," *Free-Space Laser Communication Technologies XIV*, *Proceedings of SPIE*, vol. 4639, pp. 1–15, San Jose, California, January 2002.

[181] M. Toyoshima, S. Yamakawa, T. Yamawaki, and K. Arai, "Ground-to-Satellite Optical Link Tests Between Japanese Laser Communication Terminal and European Geostationary Satellite ARTEMIS," *Free-Space Laser Communication Technologies XVI*, vol. 4635, pp. 1–15, San Jose, California, January 2004.

[182] A. Biswas and S. Piazzolla, "Deep-Space Optical Communications Downlink Budget from Mars: System Parameters," *The Interplanetary Network Progress Report 42-154*, *April–June 2003*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–38, August 15, 2003. http://ipnpr.jpl.nasa.gov/progress_report/